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A conceptual framework for design for maintainability in marine vessels: principles, barriers, and technology-driven solutions

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ABSTRACT

Design for maintainability is a systematic and proactive approach that integrates operational and maintenance considerations into the early stages of designing complex products such as marine vessels. Studies indicate that applying design for maintainability principles has a decisive impact on both the economic efficiency and operational readiness of fleets. However, traditional ship design remains primarily focused on criteria such as speed, seakeeping, and stability, while neglecting the critical role of maintainability in maritime missions. This conceptual paper, based on a systematic synthesis of literature, standards, and ship design experience, presents an integrated framework of key principles. Through thematic analysis, five fundamental principles were identified: accessibility, standardisation, modularity, reliability, and condition monitoring. Potential implementation barriers, including system complexity, budgetary constraints, siloed design practices, and human factors, were discussed alongside technology-driven solutions such as artificial intelligence, the Internet of Things, 3D printing, and digital twins. The interdependencies among the principles were also examined. This framework provides strategic guidance for designers and maintenance decision-makers, though empirical validation remains a direction for future research.

Keywords: Design for maintainability; Marine vessels; Reliability.

1 Introduction

Marine vessels are among the most sophisticated achievements of modern engineering. They operate under severe environmental conditions and therefore demand rigorous maintenance to ensure crew safety and operational effectiveness. According to available evidence, operations and maintenance expenditures for such large-scale systems may account for as much as 60% of the total life-cycle cost (1). Furthermore, the occurrence of failures within these systems can lead to considerable periods of operational unavailability (2).

However, traditional ship design often prioritises factors such as speed, seakeeping, stability, and capacity, which can result in complex systems and confined spaces, posing considerable challenges for maintenance personnel. The time expended in resolving maintenance-related problems directly diminishes fleet availability and compromises the capacity for rapid and effective operational response. System operators are keenly aware of these challenges and, prior to procurement decisions, increasingly evaluate total life-cycle cost and system availability as primary criteria (3).

The fundamental purpose of any marine system is to remain available for the execution of its intended missions throughout its designated service life. Consequently, the design process cannot be treated superficially, nor can it be reduced to the mere act of producing a deliverable asset. Rather, the provider of a marine system must be prepared to deliver support services, implement required modifications, and facilitate capability enhancements during both active operations and scheduled maintenance intervals. In response to evolving customer expectations, industrial enterprises are adopting new business models. These models move beyond conventional product sales toward integrated service packages that cover the system throughout its life cycle (2, 4). In this model, the customer pays a leasing fee that covers industrial equipment provision, maintenance, upgrades, and eventual decommissioning. As a consequence, the manufacturer assumes direct responsibility for the long-term availability of its equipment, which inevitably introduces profound maintenance-related considerations from the earliest stages of the design process (5).

Maintainability constitutes a critical element in the effective support and upkeep of any system, as well as in enabling modifications and upgrades over the system's operational lifetime. According to Gullo & Dixon (6), maintainability is a design attribute defined quantitatively as "a time-based function of the design that maximizes simplicity and gains economy of resources to restore system operation to a specified condition following the loss of critical system performance" and qualitatively as "the engineering discipline that focuses on maintenance performance by the system being designed, integrated with maintenance personnel with specialized skills and training that use prescribed maintenance procedures and support equipment at each of the designated levels of repair." Furthermore, as defined in MIL-STD-721C (6), maintainability is "a characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources."

Maintainability serves as a design parameter that guides system development toward reduced downtime and minimises the time required to restore a complex system to full functionality following a failure event (7). In accordance with the definition provided in the U.S. Navy Reliability and Maintainability Training Handbook, maintainability refers to the speed or cost associated with sustaining a system or component, or the capability of restoring it to full operational condition (8).

Within this conceptual framework, Design for Maintainability (DfM) represents an engineering philosophy and a systematic methodology that integrates operations and maintenance considerations into the early design stages of products, systems, or structures. The objective is to facilitate maintenance activities, ensure personnel safety, and minimise life-cycle costs. DfM emphasises that an item should be capable of being retained in or restored to a specified condition within a defined period, using prescribed procedures and resources, under operational conditions. This focus distinguishes DfM from reliability engineering, in that DfM is primarily concerned with recovery after failure, whereas reliability is predominantly oriented toward failure prevention.

In the course of system design, engineers must consider a multitude of factors in order to achieve an appropriate balance between design requirements and maintenance needs. Such considerations yield considerable improvements in terms of time, performance, complexity, and cost throughout the service and support life of the system, benefiting both end-users and maintenance technicians. DfM is a forward-looking and strategic approach that embeds maintenance considerations across the entire design and manufacturing life cycle of complex products, including marine vessels. This philosophy provides a set of features and combinations that render maintenance processes faster, simpler, and safer for personnel.

From a quantitative perspective, DfM delivers measurable benefits. The reduction of downtime achieved through DfM principles can lower Mean Time to Repair (MTTR) by 30% to 50% in systems that employ reliability-centred maintenance strategies (9). This figures, derived from NASA facilities maintenance guidelines (NPR 8831.2F), is based on the observation that the ratio of planned-to-reactive maintenance costs in large-scale facility operations typically ranges from 15% to 30%, indicating that transitioning from reactive to reliability-centred and condition-based strategies can reduce downtime (9). However, this reduction is context-dependent and actual improvements may vary based on the baseline maintenance maturity, system complexity, and operational environment; therefore, this range should be treated as a practical benchmark derived from NASA facility operations rather than a guaranteed outcome for all maritime systems. From a sustainability perspective, DfM facilitates component upgrading and reuse, extends service life, and reduces waste (10).

The owner of a marine asset maintains a persistent concern for product support throughout its life cycle. In many cases, particularly within the maritime sector, the support period may extend over several decades. For instance, in long-life marine systems such as surface vessels, operations and support costs are typically estimated at approximately 67% of the total life-cycle cost, and often fall within the range of 70% to 80% (11, 12). These figures are drawn from US Department of Defense guides based on historical data from major defence programmes, including naval vessels, where O&S costs consistently dominate total ownership costs (11, 12). While these estimates reflect US military practices and may differ for commercial vessels, they nonetheless provide a reliable benchmark for long-life marine systems. In contrast, design and manufacturing costs represent a relatively modest proportion of the total. Designers and ship owners must therefore identify and invest in comparatively inexpensive design measures that yield positive outcomes over decades of product support. An additional compelling rationale for establishing maintenance concepts early and incorporating DfM is that developing maintenance support infrastructure requires substantial lead time. Capabilities such as training, knowledge management systems, specialised tools, test equipment, maintenance facilities, fault diagnosis systems, spare parts inventories, and other essential elements must all

be assessed and incorporated into budgetary plans. Moreover, funding requests for approval demand rigorous analysis and comprehensive supporting documentation, which in turn require both time and specific information, including design data (13). It is noteworthy that within the U.S. Department of Defense, approximately 85% of total product life-cycle costs are typically committed and finalised during the requirements definition phase, prior to the establishment of initial design baselines (6).

The cost of design changes varies according to their nature, whether they are simple or complex, and whether they occur at the unit or subsystem level. Nevertheless, it is evident that the earlier design modifications are undertaken, the easier and less expensive the change process becomes. Embedding and deepening the maintenance concept during the early design stages permits more appropriate allocation of resources and capabilities, and facilitates the planning and budgeting processes for support infrastructure. From the standpoint of design quality, time, design costs, manufacturing costs, and maintenance costs are all of consequence. For example, the maintenance concept for a vessel's propulsion system depends on design decisions that must be made prior to the approval and finalisation of the basic design. Beyond that point, modifications become considerably more difficult, time-consuming, and costly.

Given the influence of the maintenance concept, accurate information is essential for effective design. Every member of the design team must possess the ability to understand the relationship between maintenance and product design, as well as the impact of their decisions on downstream maintenance activities. When designing a marine vessel, the team must take into account all plausible conditions that users or maintenance personnel might encounter. This investigation should address a broad range of questions concerning environmental factors. For instance, are user or maintenance activities carried out under hot and humid conditions with restricted or no easy access? Could mechanical vibrations and continuous equipment noise affect vessel personnel? Have the physical, emotional, and psychological states of the crew been considered for prolonged maritime missions and various operational tasks? Have real-world issues such as fatigue, exhaustion, stress, and workload pressures in marine environments been adequately addressed? Considerations of this nature provide all members of the vessel design team with a deeper understanding of the operational and support environments in which users and maintenance crews operate, and render them more attentive to the downstream consequences of their design choices.

By applying DfM principles, maritime personnel can realise broader strategic benefits. In other words, reduced repair and maintenance time leads to enhanced operational capability and force readiness. This ensures that marine vessels spend substantially less time in repair yards. Such an approach transforms the naval fleet into an agile and efficient force capable of executing a diverse range of maritime missions effectively. Furthermore, DfM during the design phase enables the selection of durable and maintainable components. It also minimises the need for specialised parts during operations. Easier access to equipment and workspaces, achieved through ergonomic design, enhances and improves personnel safety during vessel maintenance activities.

Within many organisations, there exists a prevailing assumption that product maintenance bears little relationship to the design function. However, research has demonstrated that for complex products such as marine vessels, this assumption is unfounded. In a considerable body of literature, design and maintenance issues have been examined sequentially and independently, even though decisions in these two domains are mutually influential (5). Embracing the DfM approach, by reducing repair and maintenance

time, strengthens fleet flexibility and operational agility, thereby ensuring high levels of operational availability.

This paper has been developed with the objective of presenting an integrated framework of key DfM principles for marine vessels. To that end, the theoretical foundations and research background in this field are first reviewed. Subsequently, five fundamental principles, namely accessibility, standardisation, modularity, reliability, and condition monitoring, are elaborated in detail. Finally, potential barriers to implementing these principles and strategies for overcoming them are discussed.

2 Literature review and theoretical foundations

The concept of DfM emerged in the aftermath of the Second World War, driven by the urgent need for rapid repairs to sustain operational readiness. During this period, ad hoc and reactive maintenance practices exposed serious deficiencies in systems such as aircraft and electronic equipment, including poor accessibility and excessive downtime. These shortcomings prompted initial efforts to embed maintainability considerations into engineering design from the outset. In the 1950s, the United States Air Force issued early guidelines for aircraft that emphasised modular designs and human factors engineering as means of reducing repair times.

The 1960s marked the formal recognition of maintainability as a distinct engineering discipline. The publication of MIL-STD-721B in 1966 established standardised terminology, defining key metrics such as Mean Time to Repair (MTTR) and integrating maintainability within the broader framework of reliability and availability (14). This standardisation arose in response to the support challenges encountered during the Vietnam War era, when support costs frequently exceeded acquisition costs by several orders of magnitude. These developments led to the formulation of predictive models and structured test procedures for assessing maintainability. In the 1980s, concurrent with the rise of Total Quality Management, maintainability principles extended into consumer products, incorporating quality circles and continuous improvement methodologies aimed at minimising life-cycle costs in manufacturing (15). This evolution signified a broader transition from reactive approaches toward proactive, interdisciplinary strategies across diverse engineering domains.

To establish the theoretical underpinnings of the subject, it is necessary to recognise that DfM refers to the systematic integration of features and considerations during the early design phase of a product, system, or structure, to facilitate and minimise the effort, time, and cost associated with future maintenance activities such as repairs, modifications, upgrades, and inspections. This approach emphasises proactive planning to ensure that systems can be serviced efficiently without requiring extensive disassembly, specialised tools, or highly skilled personnel, thereby extending operational life and reducing downtime.

The scope of DfM encompasses both preventive maintenance, which involves embedded design features that enable periodic inspections and servicing to avert failures, and corrective maintenance, which addresses issues after they have occurred. DfM distinguishes itself from reliability engineering, which is predominantly concerned with failure prevention through durable components and fault-tolerant architectures, by assuming that failures or changes will inevitably occur and focusing instead on making the responses more efficient. Similarly, DfM differs from usability, which concentrates on end-user interaction and ease of operation; rather, DfM targets the technicians and maintenance personnel who carry out post-deployment interventions. Key terminology within DfM includes standard classifications of maintenance types: predictive maintenance, which employs data and monitoring

to anticipate potential issues; preventive maintenance, which consists of scheduled actions to avert degradation; and corrective maintenance, which restores functionality after a failure.

Standard metrics quantify the impact of maintainability and provide objective criteria for design evaluation. MTTR measures the average duration required to restore a system to full operation after a failure occurs, calculated as the total maintenance time divided by the number of repairs performed. This metric reflects repair efficiency; lower values indicate more effective implementation of DfM principles. Similarly, Mean Time between Failures (MTBF) serves as a measure of system reliability, defined as total operating time divided by the number of failures experienced. Higher MTBF values indicate durable designs requiring minimal maintenance intervention. System availability is a key metric that quantifies operational readiness; however, different measures of availability apply to different analytical contexts. The commonly used relationship derived from the ratio of MTBF to the sum of MTBF and MTTR represents Inherent Availability, which assumes an ideal support environment and considers only active corrective maintenance time, excluding preventive maintenance, logistics delays, and administrative delays (16). In practice, Achieved Availability incorporates scheduled preventive maintenance and replacement of life-limited items, while Operational Availability further includes logistics delay time (waiting for spares, tools, or facilities) and administrative delay time (paperwork, scheduling, personnel availability), thus representing the actual vessel readiness in real-world operational conditions (16). Throughout this paper, references to availability are understood to mean Inherent Availability for the purpose of evaluating intrinsic design capability, with the recognition that operational planners must account for additional delays when assessing fleet-level readiness. Finally, Life-Cycle Cost (LCC) analysis, which aggregates acquisition, operation, maintenance, and disposal costs, enables economic evaluation of DfM strategies. By prioritising maintainability, designers can reduce the maintenance cost share of total life-cycle expenditure and ensure overall cost optimization (6).

Given that operations and maintenance costs typically constitute between 60% and 80% of a system's total life‑cycle cost, often reaching three times the initial construction cost, DfM becomes an inescapable necessity. Neglecting maintainability not only increases operational downtime but also compromises personnel safety. Beyond reducing repair times and enhancing system availability, DfM considerably lowers overall costs, with failure‑based strategies incurring costs up to ten times greater than preventive maintenance approaches. Furthermore, through the use of visual interfaces, DfM improves personnel safety (17).

Despite the acknowledged importance of maintainability in marine vessels, independent research in this domain remains relatively limited. One of the few studies conducted in this area is the work of Tarelko (18), who investigated mechanical equipment aboard vessels. The findings of this research indicate that the principal challenge facing the maritime industry is the absence of effective communication between design and maintenance functions, leading to low maintainability levels and costly inspection procedures. To address this problem, the study proposed a computer‑based maintainability design system comprising two modules: a data‑driven module for numerical modelling of maintainability levels, and a knowledge‑based module incorporating if‑then rules with visual recommendations. Implementation of this system on equipment such as marine engine fuel injectors demonstrated that by predicting indicators such as MTTR and identifying faults at an early stage, expensive inspections could be avoided.

The practical experience from the FFG-7 Class frigate programme demonstrated that systematic integration of maintainability requirements from

the preliminary design phase, using tools such as DCLE (Design Criteria for Logistic Elements) and Mylar overlay design control, can significantly improve equipment accessibility and removal efficiency, as validated through successful equipment removal demonstrations (19). More recent contributions include a digital mock-up and Life Cycle Performance Assessment (LCPA) approach applied to a research vessel's engine room, which demonstrated how 3D accessibility analysis can link design decisions to operational and maintenance costs (20). Additionally, a computer-aided Maintainability Design System for ship power plants was developed using formal decision-making models to support maintainability decisions from the earliest design stages (21). A comprehensive trade-off framework based on the PROMETHEE multi-criteria decision-making method was proposed for naval warship equipment, enabling designers to evaluate six alternative design solutions and select the optimal maintainability strategy (22). Furthermore, the integration of RAM (Reliability, Availability, Maintainability) principles into the ship design process has been systematically addressed through the HOLISHIP project, providing an overview of methods and tools applicable to vessel design (23). A collaborative shipyard-led research project under the US National Shipbuilding Research Program (NSRP) developed over 1,000 repair-based cost reduction strategies and delivered design rules for DfM to reduce total ownership costs (24).

Within the Iranian maritime context, Khosravifar et al. (25) conducted a comprehensive study to identify and present a design and development model for maintainability requirements in marine vessel systems. After reviewing the life cycles of similar products, they enumerated a sixteen‑phase life cycle for marine vessels, categorised into five main phases: planning, requirements definition and design problem formulation, conceptual design, preliminary and system design, and detailed design. Utilising the multi‑criteria decision‑making method TOPSIS, with weighting accomplished through Shannon entropy, they prioritised sixteen maintainability requirements and presented a final model for each design phase. According to the findings of this research, the most important maintainability requirements in marine vessel design, in order of priority, are: modularity, safety, anthropology, operation profile, system environment, parts and components, physiological factors, testability, identification, serviceability, simplicity, assemblability, accessibility, standardisation, human sensory capability, and diagnosability. The results confirm that accessibility, standardisation, and modularity, as key principles in this paper, were also prioritised in previous Iranian maritime studies. Moreover, the fact that modularity ranks as the highest-priority maintainability requirement in this study underscores the critical role of modular design in enhancing the maintainability of marine vessels.

Collectively, these studies confirm the growing recognition of DfM as a critical design discipline in marine sectors, while also highlighting the need for further domain-specific research and standardisation.

3 Key DfM principles and their impact on marine vessel maintenance

As elaborated in the following sections, the application of DfM principles, namely accessibility, standardisation, modularity, reliability, and condition monitoring, can considerably enhance the efficiency of marine vessel maintenance processes. By ensuring easy access to essential components, standardising procedures and parts, designing modular systems for rapid replacement and upgrade, prioritising system reliability to reduce failures, and implementing condition monitoring for preventive maintenance, improvements can be achieved in operational readiness, reduced downtime, and lower

maintenance costs for marine vessels, thereby increasing the reliability and service life of these valuable assets. Figure 1 illustrates the key DfM principles for marine vessels, which are examined individually in the following sections.

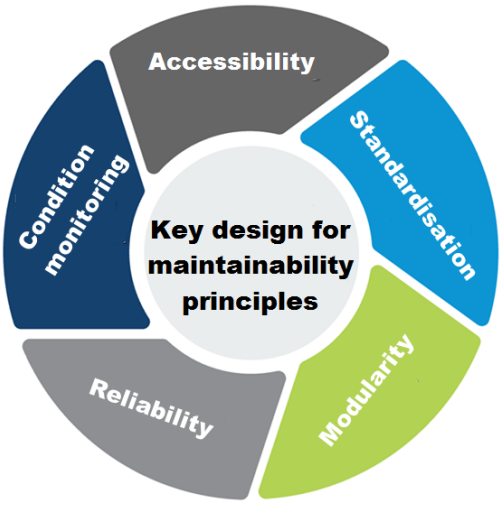


Figure 1. Key design for maintainability principles for marine vessels

Before examining each principle individually, it is important to clarify the scope of the proposed framework. The framework is intended to apply to all categories of surface vessels; however, the practical implementation of DfM principles varies considerably across vessel types due to fundamental differences in mission, regulation, design standards, and operational context. These differences must be explicitly acknowledged to ensure that designers and decision-makers can appropriately tailor the framework to their specific vessel category. Table 1 provides a structured comparison of the key characteristics that distinguish the two primary surface vessel categories, i.e., warships (combatants) and merchant ships that directly influence the applicability and prioritisation of the five DfM principles.

Table 1. Comparative characteristics of surface vessel categories relevant to DfM implementation

Characteristic	Warships	Merchant Ships
Primary Mission	Combat operations, power projection, surveillance, and deterrence (26)	Commercial cargo transport, passenger service, and trade (26)
Security Constraints	High – classified systems, restricted access, and anti-tamper requirements (27)	Low – primarily commercial security requirements
Regulatory Framework	National military standards; generally exempt from IMO/SOLAS (26, 27, 29)	IMO, SOLAS, and classification society rules (e.g., Lloyd's, DNV) (27, 28)
Redundancy Requirements	High – combat survivability, damage tolerance, and graceful degradation (26, 27)	Low to moderate – economic trade-offs; single points of failure acceptable
Crew Structure	Large crews (hundreds); specialised military training and watchstanding (26)	Small crews (25–46); commercial certification (STCW) (26)
Logistics Support	Complex – forward-deployed, at-sea replenishment, and depot-level maintenance (26)	Commercial – port-based, scheduled maintenance, and commercial supply chains
Design and Construction Standards	Stringent military standards; higher quality materials and survivability features (26)	Commercial standards; cost-driven design with less stringent requirements (29)
Cost Profile	Very high – payload and combat systems dominate (26, 27)	Lower – optimised for operational efficiency and return on investment

3-1 Accessibility

Accessibility in the context of maintenance refers to ensuring that critical components and systems can be easily reached for maintenance activities,

including routine inspections and repairs. Accessibility represents a vital aspect of DfM in the maritime industry, exerting a considerable influence on the efficiency and effectiveness of maintenance operations. Accessibility is closely related to human factors and ergonomics, as well as to layout considerations and physical constraints. The design of marine assets must take into account the physical dimensions of the human body, reachable areas, and access to work zones in order to ensure that maintenance is performed safely and efficiently.

Ergonomic design principles play a substantial role in enhancing accessibility for maintenance actions on marine vessels. By considering human factors such as reachability, visibility, manoeuvrability, and workspace ergonomics, engineers can design access points, service openings, and equipment interfaces that ensure user comfort, safety, and efficiency. For example, the ergonomic design of access panels, hatches, and doors on a vessel can reduce physical strain on maintenance personnel and enhance the productivity of these operations.

Ergonomic guidelines also promote tool-less or quick-release mechanisms, such as quarter-turn fasteners or snap-fit closures, to minimise the need for specialised tools and reduce MTTR. In marine environments characterised by adverse weather conditions, high humidity, and confined spaces, access openings should provide additional clearance for gloved hands and incorporate protection against corrosion and environmental contaminants, thereby enabling maintenance operations without interrupting vessel operations (7). These features are particularly critical for marine vessels that face harsh environmental conditions, limited equipment access, and the need for rapid at-sea repairs.

Attention to spatial layout and the arrangement of major components and systems represents one of the most fundamental steps in ensuring easy access for maintenance personnel in marine vessel design. Given the generally more constrained spaces typically found in marine vessel design, accessibility considerations assume even greater importance in these environments. Designers must ensure that maintenance personnel can move through the confined spaces of a marine vessel without compromising safety or operational efficiency, and that they can access components located in challenging areas through limited openings. The placement of essential components such as propulsion systems, electrical switchboards, machinery spaces, and mechanical equipment must be designed with great sensitivity to ensure safe and efficient maintenance operations. By optimising spatial layout and component arrangement, designers can minimise physical obstructions and establish clear pathways for maintenance personnel to access equipment effectively and perform necessary work.

Practical design and operational experience from confined engine room spaces demonstrates that accessibility challenges in marine vessels encompass a wide variety of instances. For example, the cramped space behind electrical switchboards (Figure 2) clearly illustrates how insufficient clearance for access door opening renders any repair activity difficult, sometimes even requiring the use of mirrors. Similarly, the layout of engine control rooms with corridor or U-shaped configurations (Figure 3) indicates that any repair activity effectively blocks passageways and disrupts work organisation, whereas examination of personnel movement patterns (Figure 4) shows that the absence of predesignated access routes creates a significant barrier to task performance.



Figure 2. Insufficient space behind an electrical switchboard on a vessel (30)

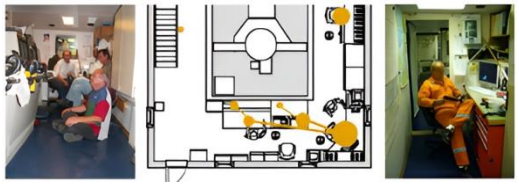


Figure 3. Engine control room with U−shaped configuration and limited space (30)

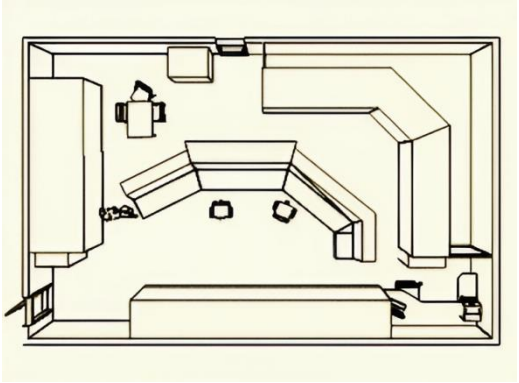


Figure 4. Personnel movement patterns within a vessel's engine control room (30)

On the other hand, field observations of repair work adjacent to consoles (Figure 5) indicate that insufficient space forces technicians into awkward postures such as cross‑legged sitting, kneeling, or crawling. Furthermore, the installation of additional equipment on walls or above consoles without considering the reach and visibility range from the primary work station represents another common challenge in this domain. These examples represent only a portion of the wide spectrum of accessibility issues encountered in practice. Under such conditions, achieving an optimal layout requires that designers anticipate personnel movement patterns and the spatial requirements of maintenance operations during the initial design phase, and provide at least the minimum clearances necessary for manoeuvring, fully opening access doors, and performing repairs without forcing personnel into awkward postures such as cross‑legged sitting, kneeling, or crawling.



Figure 5. Maintenance and repair work adjacent to vessel consoles (30)

Several important subsystems of marine vessels are examined below from the perspective of accessibility considerations:

Engine room: The engine room, as one of the most critical compartments on a marine vessel, requires regular maintenance and inspection. Appropriate engine room design, incorporating sufficient clearance for personnel manoeuvring, precise component labelling, and the provision of access openings, can improve accessibility to this area. Additionally, the creation of walkways, suitable handrails, and platforms for accessing engine room equipment can facilitate maintenance processes in this section.

Piping systems: Piping systems on marine vessels are of considerable importance and require regular

repair and maintenance. To facilitate these activities, piping design should incorporate accessible valves, connection points, and sufficient clearance for maintenance tools. Furthermore, the application of colour-coded or labelling systems in piping design can assist maintenance personnel in identifying and isolating specific components.

Deck equipment: On marine vessels, deck equipment including winches, cranes, and mooring systems are of great importance, and due to the constraints inherent in the marine environment, there is a likelihood of periodic maintenance requirements. The design of these components with clearly defined access routes, safety barriers, and ergonomic considerations can enhance accessibility.

Hull: In the event of an emergency or when underwater repairs and inspections are required on a marine vessel, the hull presents unique accessibility challenges. Efficient design incorporating features such as access hatches, underwater maintenance platforms, and remotely operated vehicles (ROVs) can facilitate and accelerate underwater maintenance and repair operations.

Marine vessels operate in dynamic and challenging environments, including severe sea conditions, and require rapid and precise maintenance to ensure operational continuity. These vessels are equipped with mission-critical systems and equipment that demand specific maintenance procedures and access considerations to ensure operational effectiveness. Operational readiness is typically the foremost priority for marine vessels, and consequently, the need for efficient access to maintenance actions to meet operational requirements and achieve mission objectives represents a persistent challenge for designers.

Based on the foregoing discussion, DfM for marine vessels in the domain of accessibility requires special considerations, some of which are listed below.

Redundancy: Marine vessels must be equipped with redundant systems to enhance survivability and mission success. DfM must ensure that redundant components and systems are readily accessible for maintenance, inspection, and replacement in order to minimise downtime and maintain operational readiness.

Security and access control: Marine vessels operate under stringent security protocols and access control measures to protect sensitive equipment and information. DfM considerations include the integration of secure access points, segregation of maintenance zones, and implementation of authorised procedures.

Safety considerations and risk mitigation: Accessibility in marine vessel design is of paramount importance and encompasses safety considerations and risk mitigation strategies to protect personnel during maintenance activities. Designers must incorporate safety regulations, ergonomic guidelines, and industry standards into the design of access points for maintenance, equipment installation, and maintenance procedures so that risks, injuries, and occupational hazards are minimised. Safety elements such as guardrails, protective barriers, non-slip surfaces, lighting, ventilation, and emergency egress routes must be considered as integral components of maintenance designs, thereby ensuring that the safety and comfort of maintenance personnel are prioritised.

3-2 Standardisation

Standardisation involves establishing common specifications, protocols, and guidelines that enable uniformity and consistency across various aspects of marine asset design and maintenance. Within the maritime industry, standardisation can encompass a wide range of elements, including materials, equipment, maintenance procedures, safety protocols, and documentation. Standardisation in marine vessel design provides interoperability and compatibility among different systems, subsystems, and equipment aboard a

vessel, thereby facilitating integration, maintenance, and upgrades. Designers tend to design marine vessels based on standard interfaces to ensure seamless connectivity, data exchange, and interoperability between various systems and components. Standard interfaces promote modularity and system extensibility, allowing maintenance personnel to readily integrate new equipment, technologies, and capabilities into existing vessel subsystems without extensive modifications or reconfiguration.

Several examples of how standardisation is employed in DfM for marine vessels are provided below.

Materials and components: Standardisation of materials used in marine vessel construction can enhance system reliability and maintainability. For instance, specifying standard steel grades for hull structures or standard types of valves and fittings in piping systems ensures consistent performance and facilitates vessel maintenance activities.

Standard spare parts: Marine vessels rely on a wide range of parts and equipment for their operations, many of which require regular maintenance and replacement. Standardisation of spare parts across a fleet or within a specific class of marine vessels can facilitate logistics, inventory management, and repair and maintenance activities. Ship designers, by specifying standard part numbers, dimensions, and suppliers for essential components such as pumps, valves, and filters, can ensure parts availability and compatibility, reduce downtime, and optimise maintenance procedures.

Maintenance procedures: Standardisation of maintenance procedures across different types of marine vessels can improve operational efficiency and safety. For example, establishing standard maintenance checklists, work instructions, and procedures for activities such as equipment inspection, lubrication, and fault diagnosis increases consistency and reduces the likelihood of errors. Standardising maintenance procedures based on industry best practices and regulatory requirements can contribute to optimised vessel performance and minimised downtime.

Documentation and data management: Standardisation of documentation and data management practices can streamline maintenance activities and facilitate information sharing. Standardising data formats, communication protocols, and component labelling methods aboard a vessel enhances interoperability and integration with maintenance management systems.

Marine vessels are equipped with mission‐critical systems and equipment that require specific standards and maintenance procedures to ensure operational effectiveness and readiness. Maintenance standardisation on marine vessels focuses on supporting the complex and diverse systems used in maritime operations. These vessels must comply with stringent maritime regulations and requirements that influence maintenance standardisation. Designing for standardised maintenance practices on marine vessels entails adherence to maritime standards, protocols, and quality assurance processes tailored to the unique operational needs of the maritime environment. Marine vessels prioritise rapid response in maintenance and operational flexibility to support mission requirements in dynamic and challenging environments. Design considerations for maintenance standardisation on these vessels emphasise agility, scalability, and adaptability to enable rapid turnaround times for maintenance actions and system upgrades, thereby sustaining operational readiness and mission success.

Examples of special DfM considerations for marine vessels in the standardisation category are provided below.

Component commonality: Marine vessels often employ standardised components and systems to streamline maintenance processes. DfM for standardisation involves the use of common parts, equipment, and systems across different vessel classes and platforms, facilitating

interchangeability, reducing training requirements for maintenance personnel, and simplifying logistics and spare parts management.

Standardised maintenance procedures: Standardisation in DfM includes the definition and implementation of consistent maintenance procedures, protocols, and guidelines across marine vessel platforms. Establishing standardised maintenance practices ensures uniformity in maintenance operations, enhances safety, reduces the risk of errors, and improves maintenance efficiency by providing clear guidelines and best practices for maintenance activities.

3-3 Modularity

Modularity is a design principle that involves decomposing a complex system into smaller, interconnected components or modules that can be readily assembled, disassembled, replaced, or upgraded. In DfM, modularity entails partitioning complex systems into independent components with loose coupling and well-defined interfaces, enabling isolated maintenance activities such as repairs or replacements without disrupting overall system function. This approach improves fault isolation, reduces MTTR, and supports life-cycle cost management by enabling targeted interventions on specific modules.

In summary, modularity in the maritime domain involves the integration of standardised, interchangeable components or subsystems to create a versatile and adaptable marine system. In the context of marine engineering, modularity plays a crucial role in enhancing the flexibility, efficiency, and maintainability of marine assets. Authoritative engineering handbooks emphasise that modularity organises components into autonomous units and minimises interdependencies, a feature that is particularly valuable in marine vessel design where rapid repairs under constrained at-sea conditions are essential.

In shipbuilding, modularity is frequently employed in vessel design and construction to improve flexibility and scalability. For example, modular vessels may feature standardised hull sections, superstructure modules, and propulsion systems that can be readily integrated or replaced to meet different mission or operational requirements. By incorporating modular components such as prefabricated cabins, equipment modules, and containerised systems, designers can achieve faster construction times, reduce maintenance costs, and facilitate future upgrades or modifications. This approach enables efficient customisation and adaptation of vessels for various operational purposes.

Modularity in marine vessel design relies on standardised interfaces, protocols, and architectures that enable seamless integration and interoperability of modular components. For instance, standardised data ports and communication protocols allow different modules, such as radar systems and sensor arrays, to exchange information and interact effectively within the vessel's ecosystem. By adopting a modular design approach, marine vessels can be readily maintained, upgraded, or repurposed throughout their operational life, resulting in cost savings, reduced downtime, and enhanced operational availability.

Modularity in marine vessel design promotes the use of interchangeable parts, assemblies, and subsystems that can be replaced to address maintenance needs or system upgrades. In the shipbuilding industry, successful examples of modularity can be observed in the design of prefabricated engine room modules, which comprise a complete set of system-related equipment, such as pumps, valves, and associated piping, mounted on a common skid and installed as a single unit within the vessel. This approach enables the replacement or repair of the entire system without accessing individual components, thereby minimising vessel downtime.

Some special DfM considerations for marine vessels in the modularity category are mentioned below:

Modular systems and components: Marine vessels can benefit from modular design for their key systems and components to facilitate maintenance processes. Modular systems enable rapid replacement of faulty parts or equipment without extensive disassembly, reducing maintenance time and enhancing operational availability.

Plug-and-Play capability: Modularity in design often includes plug-and-play features that enable rapid installation or removal of modular components. This feature allows maintenance personnel to easily replace parts and carry out maintenance actions without causing disruption.

Standard interfaces: Modular design in marine vessels often incorporates standardised interfaces between components and systems. Standardising interfaces ensures compatibility and interchangeability of modules, enabling seamless integration, fault diagnosis, and maintenance across different vessel platforms and systems. In this approach, all modules possess one or more interfaces, providing greater variety in the physical design of the product. On a marine vessel, piping and HVAC systems can benefit from standard interfaces based on specific needs and mission requirements. Figure 6 illustrates a vessel piping system with standard interfaces, representing a modular design.



Figure 6. Vessel piping system with standard interfaces (31)

3-4 Reliability

Reliability in marine vessels represents a critical aspect of product design that focuses on ensuring the performance and operational availability of vessel systems and components over time. One of the primary objectives of incorporating reliability considerations into the design process is to minimise the probability of failures or defects that could affect operational readiness, safety, and efficiency. The reliability domain in marine vessel design emphasises the selection of durable materials, standardised design practices, and proactive maintenance strategies to enhance system reliability, reduce maintenance frequency, and extend operational life cycles.

In the marine vessel design process, reliability is enhanced through the selection of high-quality, corrosion-resistant materials that are capable of withstanding corrosive marine environments, operational stresses, and dynamic loading conditions. The use of corrosion-resistant materials in critical areas such as hull structures, propulsion systems, and electrical components can reduce the risk of material degradation, premature failures, and maintenance issues arising from environmental factors or severe operational conditions. Furthermore, reliability is achieved by

incorporating redundancy and fault tolerance into essential systems to mitigate the impact of failures or defects. For example, essential systems such as propulsion and power generation often employ additional components, backup systems, and automated safety mechanisms to maintain operational continuity in the event of primary system failure. By incorporating redundancy and fault tolerance into the design process, system reliability, operational resilience, and survivability can be enhanced under challenging operational scenarios.

In the reliability domain for marine vessels, existing guidelines must be translated into specific quantitative or qualitative design criteria. An example of translating a guideline into a design criterion is as follows: avoid the use of swivel-type connectors and fittings for fuel and hydraulic line interfaces wherever possible, due to their history of low reliability. This guideline does not prohibit the use of swivel-type connectors and fittings; however, if they are used, measures must be taken to prevent the low reliability problems that have been encountered in the past.

Modern reliability in marine vessel design encompasses the use of predictive maintenance techniques, condition monitoring technologies, and data analytics to anticipate, identify, and address potential system failures before they occur. For instance, by employing advanced sensors, fault diagnosis algorithms, and predictive modelling in propulsion systems, auxiliary machinery, and electronic systems, it is possible to determine performance parameters and operational anomalies in real time. By actively identifying potential failure modes and degradation mechanisms, maintenance programmes can be optimised, downtime reduced, and overall system reliability improved. Through rigorous reliability analysis, failure mode effects and criticality analyses (FMECA), and risk assessment, designers can identify key failure modes and develop cost-effective maintenance programmes to maximise system reliability and performance.

Marine vessels are equipped with mission-specific systems and equipment that demand high reliability to support diverse operations and objectives. These vessels present unique maintenance access challenges, security constraints, and support requirements that influence reliability considerations. DfM for reliability in marine vessels involves planning for redundancy, fault tolerance strategies to meet precise performance requirements and operational demands, enhancing maintenance accessibility, providing training for maintenance personnel, and establishing robust support infrastructure to sustain operational reliability and effectiveness throughout the service life and operations of these marine assets. Based on the foregoing, special DfM considerations for marine vessels in the reliability domain are as follows.

Redundancy and backup systems: Marine vessels often employ redundant systems and backup components to ensure operational continuity in the event of equipment failure. DfM for reliability in marine vessels necessitates the incorporation of redundant systems to minimise points of failure and enhance product reliability during various missions.

Fault tolerance and self-diagnostics: Marine vessels must possess fault-tolerant designs and self-diagnostic capabilities that enable automatic fault detection and isolation within systems. Reliability considerations in marine vessel design focus on enhancing system resilience and fault tolerance to mitigate the impact of equipment failures, reduce maintenance time, and maintain operational effectiveness.

Proactive maintenance monitoring: Marine vessels should be equipped with advanced monitoring and diagnostic tools that allow maintenance personnel to actively monitor equipment performance, identify potential problems, and schedule preventive maintenance activities.

Material selection and durability: Reliability in marine vessel design is founded upon careful

selection of materials and components capable of withstanding harsh marine environments, including corrosion-resistant coatings and high-quality materials. The objective of DfM for reliability in marine vessels is to maximise durability, service life, and performance under challenging operational conditions.

3-5 Condition monitoring

Condition monitoring, as a significant topic in DfM, focuses on the integration of sensors, monitoring systems, and data analytics to enable real-time assessment of equipment health, performance trends, and operational anomalies. By incorporating condition monitoring capabilities into marine vessel design, it becomes possible to proactively identify problems, predict equipment failures, and consequently optimise maintenance programmes for vessel systems throughout their operational life. As with any strategic asset, the use of advanced sensor technologies, data acquisition systems, predictive analytics, and machine learning algorithms to monitor key parameters, assess asset condition, and support data-driven maintenance decision-making constitutes the core of condition monitoring in marine vessel design. By incorporating these technologies into the design process, designers can optimise maintenance practices and notably reduce operational costs. Some special DfM considerations and technologies for marine vessels in the condition monitoring category are discussed below.

Sensor integration and data acquisition: In marine vessel design, condition monitoring is accomplished through the integration of sensors and data acquisition systems into the vessel's primary systems. Sensors are embedded to acquire real-time data on equipment temperature, vibration, pressure, fluid levels, and other key performance indicators. By collecting and analysing sensor data, equipment health is monitored and, in the event of abnormal operating conditions being detected, early warning signs of potential failures are issued.

Predictive analytics and machine learning: By employing statistical models, trend analysis techniques, and anomaly detection algorithms on historical datasets, predictive maintenance models can be developed to forecast equipment performance and recommend maintenance actions based on asset condition trends. Machine learning algorithms can learn from historical data patterns to improve prediction accuracy, optimise maintenance schedules, and minimise downtime.

Remote monitoring and diagnostics: Advanced condition monitoring systems on marine vessels enable remote monitoring and diagnostics of equipment and systems from onboard control centres or shore-based facilities. Specialists in this field can establish remote connections, transmit data, and receive real-time alerts to monitor equipment health from a distance and diagnose problems without requiring physical inspection. Remote monitoring capabilities enhance maintenance efficiency and, by reducing response time to critical failures, enable preventive maintenance interventions to avoid unexpected breakdowns.

3-6 Interrelationships and Synergies among the Five Principles

The five principles presented above, i.e., accessibility, standardisation, modularity, reliability, and condition monitoring, do not function as isolated design criteria. Rather, they form an interdependent and synergistic system in which each principle reinforces and enables the others across the vessel's design, operation, and maintenance lifecycle. Understanding these interrelationships is essential for effective implementation of the framework.

To properly appreciate the interdependencies among the five principles, it is first necessary to

distinguish four foundational concepts that are often conflated in practice. According to Gullo & Dixon (6), maintainability is defined as "a time-based function of the design that maximizes simplicity and gains economy of resources to restore system operation to a specified condition following the loss of critical system performance." This definition emphasises that maintainability is fundamentally about recovery after failure (the speed and ease with which a system can be returned to operational status). In contrast, reliability, as defined by Lalli& Packard (16), concerns failure prevention: "the chance of a failure that will stop the system from operating." Reliability is typically quantified by MTBF, whereas maintainability is quantified by MTTR. Availability, from the same NASA source, is "the probability of the system being ready to operate when needed," which is mathematically derived from the combination of MTBF and MTTR. Finally, supportability encompasses the broader logistics and infrastructure elements that enable maintenance to be performed effectively. As elaborated in (6) and (16), supportability includes spare parts provisioning, tools, test equipment, training, technical documentation, facilities, and supply chain management. While maintainability addresses how easily a system can be repaired, supportability addresses whether the resources exist to perform that repair when and where it is needed.

A fundamental principle governing the relationship between reliability and maintainability is articulated by Gullo & Dixon (6): "Maintainability is inversely proportional to reliability." The authors elaborate: "As reliability goes up, maintainability goes down. As more system or product failures occur, the calculated reliability of a system goes down and the quantity of maintenance actions goes up." This inverse relationship reflects a critical design trade-off: improving reliability (reducing failure frequency) typically requires investment in higher-quality components, redundancy, or more robust design, which may reduce the need for maintenance but does not necessarily make maintenance easier. Conversely, a system with inherently lower reliability must be designed for rapid and easy repair (high maintainability) to maintain acceptable availability. The designer's task is to strike an optimal balance between these two competing objectives based on mission requirements, operational constraints, and life-cycle cost considerations.

The inherent tension between reliability and maintainability is effectively reconciled through condition monitoring, which serves as the operational bridge connecting the two domains. Condition-based maintenance (CBM) enables smart decision-making by continuously monitoring asset condition, processing real-time data to detect anomalies, and alerting operators and maintainers before functional failure occurs (6). By detecting degradation trends early, condition monitoring allows maintenance to be scheduled proactively rather than reactively, thereby supporting reliability by preventing unexpected failures and extending component life, while simultaneously enhancing maintainability by enabling planned, non-emergency repairs with better resource allocation and reduced downtime. Thus, condition monitoring transforms the inverse relationship between reliability and maintainability into a complementary relationship: it compensates for inherent reliability limitations through intelligent, data-driven maintenance planning.

While redundancy and fault tolerance are sometimes treated as independent design principles, in the present framework they are understood as tactical design choices embedded within the broader principles of modularity and accessibility. As discussed in (6), fault-tolerant architectures enable a system to continue operating despite component failures. This capability supports both reliability (continuous operation in the presence of failures through graceful degradation rather than catastrophic

shutdown) and maintainability (the ability to replace failed modules without full system shutdown through hot-swap capability). These tactics are most effectively implemented through modular design, where standardised interfaces allow rapid removal and replacement of Line Replaceable Units (LRUs) or Orbital Replaceable Units (ORUs), and through accessibility provisions that enable maintainers to reach backup components without disassembling unrelated systems.

Standardisation plays a uniquely enabling role across multiple dimensions of the framework. By establishing common specifications for parts, interfaces, procedures, and documentation, standardisation simultaneously enhances supportability (common parts reduce supply chain complexity, simplify inventory management, and facilitate procurement), improves maintainability (standardised fasteners, connectors, and tools reduce the variety of tools required and simplify training), supports reliability (standardised components with known performance histories enable more accurate reliability predictions), and facilitates modularity (standardised interfaces allow interchangeable modules from multiple suppliers). The practical importance of standardisation was demonstrated in the FFG-7 project, where the systematic use of DCLE (Design Criteria for Logistic Elements) summary sheets and equipment categorisation into removal categories A, B, C, and D enabled consistent maintenance planning across approximately 850 equipment items (19). This standardised approach ensured that removal routes, handling equipment, and maintenance procedures could be developed systematically, reducing both planning effort and execution time.

In summary, the five principles function as a coherent system where each element contributes to and depends upon the others, as illustrated in Table 2.

Table 2. Interdependencies among the five DfM principles

Principle	Primary Role	Key Dependency
Accessibility	Physical access for inspection, repair, and replacement	Enabled by Modularity (separate modules) and Standardisation (common access methods)
Modularity	Rapid replacement and upgrade	Requires Standardisation (interfaces) and Accessibility (reachable modules)
Standardisation	Consistency, interoperability, and logistics efficiency	Supports all other principles
Reliability	Reducing failure frequency	Supported by Condition Monitoring (early detection) and Modularity (graceful degradation)
Condition Monitoring	Predicting and preventing failures	Relies on Accessibility (sensor placement) and Standardisation (consistent data formats)

This interdependence ensures that the framework is not merely a checklist of desirable features but a strategically integrated approach to vessel design that optimises operational availability, reduces life-cycle costs, and enhances crew safety. The practical value of this integrated approach is validated by the FFG-7 experience, where the concurrent implementation of accessibility, modularity, standardisation, and reliability considerations resulted in successful maintainability demonstrations and improved fleet readiness (19).

4 Potential barriers to implementing DfM in marine vessels and technology-driven solutions to overcome them

Those responsible for implementing DfM in marine vessels may encounter various obstacles and

constraints throughout the process. One significant challenge is the complexity and interdependence of systems aboard marine vessels, which can make it difficult to identify and prioritise maintenance requirements. Overlooking the training needs of end-users and maintenance personnel is a common oversight that can lead to improper use, increased downtime, or safety hazards during repairs. Systems designed without considering operator skill levels may demand expertise that is not available in operational environments. The complex design of engine control systems on some commercial vessels, developed without regard for the skill levels of maintenance crews, has resulted in delayed fault diagnosis and extended vessel downtime in ports. This problem often arises when maintainability is treated as an afterthought and the influence of human factors on long-term system usability is neglected.

Furthermore, stringent safety and security regulations within the maritime industry can impose constraints on design modifications required for maintainability improvements. Siloed design practices, in which interdisciplinary maintenance aspects are overlooked, represent another common error that leads to misalignment between software and hardware components and complicates fault diagnosis or repairs. In isolated development approaches, different engineering disciplines fail to integrate reliability, logistics, and operations at an early stage, resulting in fragmented systems with poor fault isolation or inaccessible components (32). In the design of certain naval vessels, the separation of electronic systems design from mechanical systems design has created fault diagnosis blind spots and increased repair times under operational conditions. In some cases, the inappropriate placement of electrical switchboards behind piping systems has made safe access for repairs problematic. Budgetary constraints also limit the adoption of advanced maintainability-friendly technologies, and the need to meet high performance standards and operational requirements sometimes takes precedence over maintenance considerations, leading to engineering trade-offs in design. In the design of high-speed craft, the emphasis on weight reduction and speed enhancement may lead to the use of materials and connections that restrict equipment access and complicate maintenance operations.

Addressing these barriers and constraints demands a systematic approach. The formation of interdisciplinary design teams comprising representatives from engineering, operations, logistics, and maintenance from the conceptual stage is essential for aligning with support requirements. Iterative prototyping combined with maintenance simulations, such as failure mode and effects analysis (FMEA), allows teams to identify and rectify accessibility or training gaps at an early stage, thereby reducing MTTR. Implementing mandatory design reviews, in accordance with structured programmes such as the Maintainability Design Program, along with trade-off studies that balance performance against total cost of ownership, further enhances accountability (32). In the design of modern vessel engine rooms, the use of three-dimensional (3D) simulations during the early design stages has enabled the identification of difficult access points and prevented costly modifications in later stages.

To move beyond descriptive generalities and address the repetitive nature of the previous discussion, the barriers identified above are systematically analysed through a structured cause-consequence-solution framework, as shown in Table 3. This matrix transforms the discussion into an actionable, principle-based decision tool that designers and project managers can directly apply to vessel development programmes. Each barrier is mapped to its root cause, operational consequence, and targeted solution linked to one or more of the five DfM principles. The solutions range from design-phase interventions (modularity, accessibility validation) to operational-phase

measures (condition monitoring, LCC‑based trade‑offs), all aligned with the strategic framework presented earlier.

Table 3. Barrier-Cause-Consequence-Solution Matrix for DfM implementation in marine vessels

Barrier	Root Cause	Consequence	Solution (Linked to DfM Principle)
System Complexity	Interdependent systems with high coupling	Increased fault diagnosis time; extended troubleshooting	Modularity – decouple systems into independent modules with standard interfaces
Budgetary Constraints	High upfront DfM investment costs	Limited adoption of advanced technologies; design trade-offs favour performance over maintainability	Life-Cycle Cost (LCC) analysis integrated with Reliability principles
Siloed Design Practices	Poor interdisciplinary communication	Misalignment between hardware, software, and logistics; inaccessible components	Accessibility – enforce interdisciplinary design reviews; use 3D simulations for spatial validation
Human Factors Neglect	Insufficient operator/maintainer training	Improper maintenance; increased downtime; safety hazards	Human-centred design embedded within Accessibility and Standardisation
Regulatory Gaps	Lack of dedicated maintainability standards for marine vessels	Inconsistent DfM implementation across shipyards; compliance uncertainty	Positioning the framework relative to IEC, IMO, SOLAS, and ASTM as a bridging guide
Data Scarcity	Lack of field performance feedback	Unvalidated maintainability predictions; reactive maintenance persists	Condition Monitoring – embed sensors; implement CBM+ and PHM with ML-based diagnostics

Today, emerging technologies are transforming DfM through the integration of intelligent systems. Artificial intelligence and machine learning, by detecting anomalies in sensor data, enable the prediction of equipment degradation before failure occurs, as demonstrated in recent maritime studies (33-36).

Beyond internal stakeholder collaboration and procedural standardisation, however, the proposed framework must also be positioned relative to the international standards and regulatory instruments that govern vessel design, operation, and maintenance. IEC 60300-3-10:2025 provides guidance for implementing a maintainability programme throughout the design and operational phases, thereby supporting the standardisation and modularity principles of the framework, though its full application is best suited to complex, long-life vessels (37). IEC 60300-3-2:2004 reinforces the condition monitoring principle through guidelines for field data collection on reliability, maintainability, and availability, but assumes a mature data-collection infrastructure which may not be available to all vessel operators (38). The IMO ISM Code, mandatory under SOLAS Chapter IX, establishes a safety management system (SMS) with Section 10 requiring planned maintenance and identification of critical equipment, providing a management framework for safe ship maintenance, though its focus is on operational processes rather than technical design features (39). SOLAS Chapter II-1, Regulation 3-13, effective from January 2026, imposes structured requirements for the design, construction, testing, and maintenance of lifting appliances with SWL ≥ 1,000 kg, directly impacting vessel design and reinforcing the accessibility principle in this

specific domain, though its scope is limited to lifting equipment (40). ASTM F2446-04(2026) supports the standardisation and condition monitoring principles by providing a hierarchical nomenclature and data exchange standard for RAM performance data across shipbuilding and operations stakeholders, though it addresses data exchange rather than prescriptive design rules (41). As this brief review reveals, there exists a notable fragmentation and gap in the current standards landscape for marine vessel maintainability: no single standard comprehensively addresses all five strategic principles (accessibility, standardisation, modularity, reliability, and condition monitoring) in an integrated manner, and the existing instruments are either generic (IEC), management-oriented (ISM), narrowly scoped (SOLAS II-1/3-13), or data-centric (ASTM). This fragmentation necessitates that vessel designers and operators navigate a patchwork of requirements, often leaving practical design decisions for maintainability unsupported by unified regulatory guidance. Consequently, there is a clear and urgent need for the development of a dedicated, comprehensive international standard for marine vessel maintainability that integrates technical design principles, operational maintenance requirements, and regulatory compliance into a single cohesive framework tailored specifically to the maritime industry. Such a standard would address the identified gap by providing clear, actionable design criteria that align with the five principles proposed in this framework, thereby enabling vessel designers to make informed, standardised decisions that enhance operational availability, reduce life-cycle costs, and improve safety across the fleet.

In the shipbuilding industry, machine learning algorithms that monitor the condition of main engines can predict imminent failures and enable repairs to be scheduled during planned stoppages (42). The Internet of Things (IoT), with its networks of sensors, facilitates real‑time tracking of asset conditions and, by collecting metrics such as vibration, temperature, and power consumption, enables data‑driven decision‑making (43). On marine vessels, IoT‑based sensor networks installed on critical equipment such as generators, pumps, and HVAC systems enable continuous monitoring of operational parameters (44). The installation of vibration sensors on vessel shaft bearings facilitates early detection of wear and enables timely bearing replacement planning.

Additive manufacturing (3D printing), with its capability for rapid production of custom parts using computer models, which reduces production time compared to conventional methods, can address the challenges of spare parts supply in remote maritime environments (45). According to available reports, some shipping companies have installed 3D printers aboard their vessels, enabling the production of required parts such as piping fittings and plastic components for HVAC systems at sea, thereby minimising dependence on external suppliers (46). Digital twins, by simulating maintenance scenarios and predicting failures, improve design iterations for enhanced accessibility and efficiency (47). The creation of digital twins for vessel engine rooms enables the simulation of various operational conditions and the prediction of equipment behaviour prior to failure, revealing design weaknesses (48).

Beyond these digital and additive technologies, emerging smart materials offer additional capabilities that directly support the maintainability of marine vessels. Piezoelectric sensors can be embedded in or attached to critical load-bearing structures such as hulls, propeller blades, and deck panels to directly measure strain, stress, and acoustic emissions caused by fatigue, corrosion, or impact loads (49, 50). Recent research has demonstrated the feasibility of using embedded piezoelectric sensors for acoustic emission monitoring of composite marine propellers in submerged conditions, enabling early detection of damage development within the composite material (51). Further`more, advanced

piezoelectric sensor systems have been developed as "Fitbit-for-structures" devices capable of measuring complex loading conditions and converting them into fatigue damage indices for predicting the remaining service life of ship structures (52). These capabilities enable continuous, in-service assessment of structural integrity, allowing maintenance to be planned based on actual condition rather than fixed schedules, thereby directly reinforcing the condition-based maintenance philosophy central to DfM.

An emerging approach to further improve accessibility for maintenance personnel involves the use of shape memory alloy (SMA)-based fasteners and connectors, which are increasingly finding applications in marine environments (53). These smart components can be designed to exhibit a two-way shape memory effect, enabling them to generate significant recovery forces for secure fastening while also being releasable or adjustable through controlled temperature variations. Novel C-shaped SMA connectors have been investigated for their potential to provide reliable, reusable connections in demanding applications, including marine and aerospace systems (54). For marine vessels, SMA fasteners could be employed in access panels, equipment mounts, and modular connections that require frequent opening for inspection or replacement. By allowing remote or rapid release without specialised tools, these fasteners reduce the physical effort and time required for maintenance tasks, particularly in confined or hard-to-reach spaces such as engine rooms. This technology directly supports the accessibility principle of DfM by transforming traditionally fixed connections into adaptive, user-friendly interfaces that enhance both maintenance efficiency and personnel safety.

In summary of the discussions presented above, it can be concluded that overcoming the barriers to implementing DfM in marine vessels requires a combination of structural, technical, and technological measures. At the structural level, the formation of interdisciplinary teams, mandatory design reviews, and standardisation of procedures provide the necessary foundation for integrating maintenance considerations. At the technical level, the use of 3D simulations and life‑cycle cost analyses during the early design stages enables early identification and correction of weaknesses. At the technological level, the adoption of artificial intelligence, the IoT, 3D printing, digital twins, and other innovations has transformed maintenance approaches, transforming them from reactive to preventive and predictive.

By adopting this comprehensive and integrated approach, marine vessel designers will be able to identify and address existing obstacles, considerably enhance maintenance operation efficiency, and design vessels with higher operational readiness, lower life‑cycle costs, and greater personnel safety. The future of DfM for marine vessels is moving toward ever‑greater utilisation of intelligent technologies and data‑driven approaches, and it is expected that with the evolution of these technologies, we will witness a considerable reduction in downtime, extended equipment service life, and optimised resource consumption across marine fleets.

5 Conclusion

Based on the discussions presented in this paper, it can be concluded that applying Design for Maintainability (DfM) principles and approaches to marine vessels is essential for maritime organisations seeking to improve operational efficiency and enhance readiness. By emphasising the importance of accessibility, standardisation, modularity, reliability, and condition monitoring within the design framework, maritime stakeholders can improve maintenance protocols, reduce operational downtime, and maximise the availability of marine assets. This proactive approach not only proves effective in reducing product life-cycle costs but also plays a significant

role in strengthening operational readiness and the effectiveness of maritime assets. Accordingly, in marine vessel design, the important matter of accessibility for maintenance operations is prioritised, with emphasis on rapid access to key systems, special attention to redundancy requirements, integration of security measures, and consideration of environmental and operational factors. Focus on standardisation of maintenance methods, promotion of modularity in vessel structures and systems, employment of standard interfaces, and scalability constitute other important principles. Reliability, as one of the essential principles in DfM for marine vessels, is enhanced through measures such as focusing on design concepts including redundancy, fault tolerance, preventive maintenance monitoring, and selection of appropriate and durable materials. It can be asserted that embracing the DfM philosophy emerges as a pivotal mechanism in empowering the maritime domain to sustain operational flexibility.

However, the path toward realising these objectives is accompanied by obstacles such as system complexity, budgetary constraints, siloed design practices, and insufficient attention to human factors. What makes these obstacles surmountable is the adoption of a holistic and multi-level approach that, on the one hand, provides the structural and technical foundation through the formation of interdisciplinary teams, mandatory design reviews, and 3D simulations in the early stages, and on the other hand, revolutionises maintenance approaches by leveraging 4th-generation technologies such as artificial intelligence, IoT, 3D printing, and digital twins. These technologies transform maintenance from a reactive state to preventive and predictive, and by enabling real-time monitoring, failure prediction, and on-demand part production, they reduce dependence on traditional supply chains and minimise operational downtime. It is important to acknowledge the limitations of this study: the findings are derived from a conceptual synthesis of existing literature and established standards, and while the proposed framework provides strategic guidance for designers and decision-makers, its practical effectiveness and quantitative benefits require empirical validation through case studies and field applications.

The findings also point to several research gaps that warrant further investigation. Key among these are the need for empirical validation of the framework through practical case studies across different vessel types, the development of quantitative models to capture trade-offs among the five principles, the integration of smart materials for structural health monitoring and adaptive fastening, the establishment of a unified international standard for marine maintainability, and greater attention to the human and organisational dimensions of DfM implementation. Addressing these gaps through collaborative efforts between academia, industry, and regulatory bodies will be essential to advance the field.

Looking ahead, the future of DfM for marine vessels is likely to be shaped by the continued integration of intelligent technologies and data-driven approaches. While technologies such as self-diagnosing systems, self-healing materials, and AI-driven predictive maintenance offer promising potential, their maritime applications remain in early stages of research and development, and their operational feasibility requires further investigation. With continued research and development, the maritime industry may progressively move toward a new generation of vessels in which maintainability is systematically embedded as a core design parameter, contributing to enhanced operational readiness, reduced life-cycle costs, and improved sustainability across naval and commercial fleets.

6 References

[1] Dhillon BS. Maintainability, maintenance, and reliability for engineers: CRC press; 2006.

[2] Markeset T, Kumar U. Design and development of product support and maintenance concepts for industrial systems. Journal of Quality in Maintenance Engineering. 2003;9(4):376-92.
[3] Rawat M, Lad BK. Simultaneous selection of reliability design and level of repair for fleet systems. International Journal of System Assurance Engineering. 2016;7(2):138-55.
[4] Lesobre R, Bouvard K, Bérenguer C, Barros A, Cocquempot V, editors. A maintenance free operating period policy for a multi-component system with different information levels on the components state. PHM2013-2013 Prognostic and System Health Management Conference; 2013: AIDIC Servizi.
[5] Adjoul O, Benfriha K, Aoussat A. Design for maintenance: new algorithmic approach. Journal of quality in maintenance engineering. 2021;27(1):129-43.
[6] Gullo LJ, Dixon J. Design for maintainability: John Wiley & Sons; 2021.
[7] US Department of Defense. Designing and Developing Maintainable Products and Systems MIL-HDBK-470A. Washington DDoD. 1997.
[8] Winlund ES. NAVSHIPS 0900-002-3000: Reliability and Maintainability Training Handbook. PN U. 1964.
[9] NASA. Facilities Maintenance and Operations Management: NPR 8831.2F. Washington, DC: NASA; 2015 [Available from: https://nodis3.gsfc.nasa.gov/displayDir.cfm.
[10] Herbert LS. Designing for reliability, maintainability, and sustainability (RM&S) in military jet fighter aircraft engines: Massachusetts Institute of Technology; 2002.
[11] US Department of Defense. Operating and Support Cost-Estimating Guide Washington, DC: Department of Defense; 2014.
[12] US Department of Defense. Operating and Support Cost Management Guidebook. Washington, DC: Department of Defense; 2016.
[13] GAO. BEST PRACTICES: Setting Requirements Differently Could Reduce Weapon Systems' Total Ownership Costs. US Government Accountability Office Washington, DC; 2003.
[14] Standard M. Definitions of Terms for Reliability and Maintainability. Washington, DC: Department of Defense; 1981.
[15] Total Quality Management [Internet]. Milwaukee (WI): American Society for Quality 2026 [Available from: https://asq.org/quality-resources/total-quality-management.
[16] Lalli VR, Packard MH. Designing for maintainability and system availability. 1997.
[17] Sild S. Design for Maintenance Principles Explained 2023 [Available from: https://fractory.com/design-for-maintenance/.
[18] Tarelko W. The improvement of ship mechanical equipment maintainability through design. WIT Transactions on The Built Environment. 2026;5.
[19] Guido AJ, Light SP. Ship design for maintainability: Experience on FFG 7 class. Naval Engineers Journal. 1978;90(2):75-84.
[20] Notaro C, Gualeni P, Maggioncalda M, Cau C. Design for Maintainability of a Research Vessel's Engine Room. A Holistic Approach to Ship Design: Volume 2: Application Case Studies: Springer; 2021. p. 133-69.
[21] Tarelko W, editor Modelling of decision-making process relating to design for maintainability of complex technical items. Engineering Systems Design and Analysis; 2008.
[22] Zheng S, Chen G, Zhang Y. Maintainability analysis and comprehensive tradeoff of naval ships equipment based on PROMETHEE method. Journal of Control Decision. 2024;11(3):375-84.
[23] Le Diagon V, Li N, Klein L, Corrignan P. Application of reliability, availability and maintenance principles and tools for ship design. A Holistic Approach to Ship Design: Volume 1: Optimisation of Ship Design and Operation for Life Cycle: Springer; 2018. p. 357-81.
[24] Dlugokecki V, Fanguy D, Hepinstall L, Tedesco M, editors. Reducing the Cost of Ship Maintenance and Repair. SNAME Maritime Convention; 2014: SNAME.
[25] Khosravifar M, Karbasian M, Nilipour Tabatabaee A. Investigating and Proposing a Design Model and Development of Maintainability Requirements for a Vessel Marine Systems Using MCDM Approach. Hydrophysics. 2020;6(1):95-111.
[26] Birkler J. Differences between military and commercial shipbuilding: applications for the United Kingdom's Ministry of Defence: Rand Corporation; 2005.
[27] Delpizzo RD, Valluri S. An introduction to NATO standard ANEP (allied naval engineering publication) 77 and its application to naval ships. Ship science technology. 2017;11(21):75-88.

[28] DALEY C, KENDRICK A. Comparative Study of Naval and Commercial Ship Structure Design Standards. 2007.
[29] Dunn Jr JP. A Comparative Analysis of Naval Auxiliary and Merchant Ship Design. 1978.
[30] Wagner E LM, Grundevik P. Engine Control Rooms - Human Factors: Field Studies. Sweden / Chalmers University of Technology; 2008.
[31] Erikstad SO. Design for modularity. A Holistic Approach to Ship Design: Volume 1: Optimisation of Ship Design and Operation for Life Cycle: Springer; 2018. p. 329-56.
[32] Vincent R. Design for reliability: NASA reliability preferred practices for design and test. NASA TM-106313; 1994.
[33] Maione F, Arici SS, Hasan A, Sukarevicius M, Akyuz E, Karlsen A. Agentic AI for autonomous condition monitoring and predictive maintenance of marine vessels. Ocean Engineering. 2026;364:127078.
[34] Maione F, Lino P, Maione G, Giannino G. A machine learning framework for condition-based maintenance of marine diesel engines: a case study. Algorithms. 2024;17(9):411.
[35] Wang B, Wang Z, Yao C, Chen J, Lu L, Song E. Multi-system condition monitoring of marine engines: A unified deep learning framework introducing physical prior knowledge. International Journal of Naval Architecture. 2025:100698.
[36] Je-Gal H, Park Y-S, Park S-H, Kim J-U, Yang J-H, Kim S, et al. Time-series explanatory fault prediction framework for marine main engine using explainable artificial intelligence. Journal of Marine Science Engineering. 2024;12(8):1296.
[37] IEC 60300-3-10:2025. Dependability management – Part 3-10: Application guide – Maintainability and maintenance. International Electrotechnical Commission, Geneva; 2025.
[38] IEC 60300-3-2:2004. Dependability management – Part 3-2: Application guide – Collection of dependability data from the field. . International Electrotechnical Commission, Geneva; 2004.
[39] IMO. International Safety Management (ISM) Code. International Maritime Organization, London. Made mandatory through SOLAS Chapter IX.
[40] SOLAS Chapter II 1, Regulation 3 13 – Lifting Appliances and Anchor Handling Winches. . International Maritime Organization, Resolution MSC.532(107); 2026.
[41] ASTM F2446 04(2026). Standard Classification for Hierarchy of Equipment Identifiers and Boundaries for Reliability, Availability, and Maintainability (RAM) Performance Data Exchange ASTM International, West Conshohocken, PA; 2026.
[42] Michel M, Mehanna A, Saleh SN, Shehata AS. Proactive fault prediction in marine diesel engines using multivariate machine learning. Scientific Reports. 2026;16(1):9678.
[43] Jia J, Wang J, Liu Y, Zhu L, Chen B, Ao N, et al. Intelligent Maritime Wireless Sensing for Smart Vessels: Perspective, Architecture, and Challenges. IEEE Wireless Communications. 2025.
[44] Anitha K, Vijayakumar R, Jeslin JG, Elangovan K, Jagadeeswaran M, Srinivasan C, editors. Marine propulsion health monitoring: Integrating neural networks and IoT sensor fusion in predictive maintenance. 2024 2nd International Conference on Device Intelligence, Computing and Communication Technologies (DICCT); 2024: IEEE.
[45] Falkonakis I, Lotfian S, Yeter B. Multi-criteria decision analysis of an innovative additive manufacturing technique for onboard maintenance. Sustainability. 2024;16(9):3763.
[46] Kostidi E, Nikitakos N, Lilas T, Dalaklis D, Research. Stakeholders' perceptions on the introduction of additive manufacturing (AM) in the maritime spare parts supply chain. J Maritime Technology. 2024;6(2):268186-.
[47] Bertagna S, Braidotti L, Bucci V, Marinò A. An innovative methodology for enabling predictive maintenance of ship systems based on Industry 4.0 technologies. Procedia Computer Science. 2025;253:2389-98.
[48] Jeon J, Theotokatos G. A framework to assure the trustworthiness of physical model-based digital twins for marine engines. Journal of Marine Science Engineering. 2024;12(4):595.
[49] Huijer AJ. Structural health monitoring of composite marine propellers using embedded piezoelectric sensors [Ph.D]: Delft University of Technology; 2025.
[50] Roch E, Zima B, Woloszyk K, Garbatov Y. Guided waves in ship structural health monitoring–A feasibility study. Polish Maritime Research. 2023;30(2):76-84.
[51] Huijer A, Kassapoglou C, Pahlavan L, Structures. Acoustic emission monitoring of composite marine propellers in submerged conditions using embedded piezoelectric sensors. Smart Materials. 2024;33(9):095018.

[52] Ghaderiaram A, Mohammadi R, Schlangen E, Fotouhi M. Development of an innovative extension for fatigue life monitoring using a piezoelectric sensor. Procedia Structural Integrity. 2024;52:570-82.
[53] Niccoli F, Scalet G, Giovinco V, Garion C, Maletta C, Chiggiato P, et al. Novel C-Shaped shape memory alloy connectors for vacuum flanges: modeling and tests. Shape Memory and Superelasticity. 2023;9(4):546-57.
[54] Guo J, Pan B, Cui W, Xiang H, Engineering. Modeling and Analysis of Resistance-Sensing Characteristics for Two-Way Shape Memory Alloy-Based Deep-Sea Actuators. Journal of Marine Science Engineering. 2024;12(10):1703.