Use of Additive Technologies for the Accelerated Production of Spare Parts for Marine Hatches

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Abstract: ***This paper discusses the use of additive technologies in the fast production of spare parts for watertight ship hatches. The main goals are to conduct a multi-perspective review on regulatory, technological, and economic appropriateness of using additive manufacturing in making hatch locking hardware and seals; to validate materials and process options by requirements of Classification Societies; and finally, to formulate practical recommendations regarding steps toward actual integration of the distributed fleet printing stations into ship repair and also planned preventive maintenance of fleets. There have been such losses that it raised the level of consciousness for change from unplanned downtimes, plus global fleet aging against traditional supply chains being inadequate and not responding with ship operability restoration in a short time. That which is novel herein comprises empirically synthesizing the latest versions of Guidance Notes and certification programs from Lloyd's Register and DNV, together with precedential examples, industrial accreditation, plus deployment, and showing polymer and metal AM solutions for critical marine assemblies. Requirements specifically related to PQ/MQ and the Build Report are compared systematically with test results on the most up-to-the-minute materials. Technological impacts are quantitatively estimated out of this process while simultaneously demonstrating digital operating models whereby a catalog of protected CAD files replaces the physical warehouse and production moves to the place needing repair. The paper finds that printed plastic and metal components can meet the performance standards of cast and forged parts when produced under strict process and raw-material control, validated by appropriate non-destructive testing and post-processing. This paper will be useful for engineering assistance alongside and aboard at the shipyard, operators of a fleet, manufacturers of additive equipment and material, representatives from a Classification Society who are actively involved in developing qualification practices, and regulators, while trying to implement distributed AM services.***

Keywords: additive technologies, 3D printing, watertight hatches, spare parts, process qualification, Lloyds Register, DNV, PA12-CF, PEKK, LPBF, WAAM, topology optimization, digital warehouse

1. Introduction

In the contemporary maritime environment, operational resilience has emerged as a crucial determinant of economic viability and seaborne safety, such that localized mechanical failures—seemingly discrete in nature—propagate into systemic disturbances that imperil schedule integrity, contractual performance, and institutional reputation. These cascading effects expose a latent fragility in conventional maintenance paradigms: the temporal and logistical inertia intrinsic to traditional spare-parts provisioning translates structural decay into acute operational crises, thereby converting intermittent hardware degradation into a strategic continuity problem rather than a mere engineering nuisance.

There is, therefore, a compelling requirement to rethink parts supply and maintenance operations as components of a human-centered technical support system that can be quickly reconfigured under challenging conditions. Additive manufacturing, governed within an environment of digital rights management, process qualification, and monitored post-processing, provides for more than just make-do production. It becomes one way to redesign stock into a secure, version-controlled body of executable digital objects and to shift production to the point where it is needed. The major problem thus becomes not merely technological but organizational and regulatory: to print parts with repeatable performance entails calibrated process governance, metrological rigor, and normative acceptance, together with human capital investment and cyber-secure digital warehousing.

The framing thus locates the ensuing review within a problem-centered logic-it interrogates the extent to which and how additive technologies may be applied toward compression of repair leadtimes as well as amelioration of such systemic risks articulated above by bringing into play criteria for qualification, pathways for staged integration, and institutional prerequisites needed to transform an emergent manufacturing capability into a dependable tool of fleet resilience.

Watertight hatches are critical elements of a ship's hull strength and fire safety, so their failure instantly translates into downtime: a ship cannot leave the berth until a worn latch or a clamping bracket is replaced. MaintainX analytics for 2024 show that the average hour of unplanned equipment downtime costs operators approximately 25,000 USD, and for large fleets, this amount can exceed 500,000 USD [1].

The age of the fleet exacerbates the problem: according to a joint study by the Maritime and Port Authority of Singapore and DNV GL, the global fleet spends about 13 billion USD annually on spare parts, with half of the ships over 15 years old, which makes original hatch parts either scarce or completely unavailable due to lost tooling [2]. Under such conditions, the classical supply chain—from ordering at a foundry to delivery through several port agents—stretches out and requires maintaining an expensive physical warehouse.

Additive technologies dramatically upend this picture: the command of the U.S. Navy strategic submarine program noted that switching to printing metal bolts and latches reduced new part delivery time to the ship by approximately 80% as compared to traditional casting and machining [3].

When geometry is stored not in metal but rather in a protected CAD file, inventory changes from physical nomenclature to a digital catalog, and fabrication moves right to the ship repair yard or even on board.

The regulatory framework for such a transition is being formed at an accelerated pace: the July update of the Guidance Notes by Lloyd's Register regulates qualification of polymer and metal AM processes for marine applications, including requirements for feedstock traceability and non-destructive testing of finished parts, and LR's global service program for certification of AM components already covers hatch locking hardware [4].

Thus, the task of accelerating fleet repairs today is solved at the intersection of three vectors: economic pressure from downtime, technological readiness to print stainless or duplex steels with the required tightness, and regulatory support ensuring the trust of classification societies. These factors make the use of additive manufacturing for hatch spare parts not an experiment but a logical stage in the evolution of ship maintenance.

2. Materials and Methodology

This study relies on a comprehensive analysis of regulatory documents, industry reports, empirical deployment cases, and materials science publications, as well as on the synthesis of qualification practices and digital part preparation applicable to additive manufacturing of spare parts for watertight hatches. The key regulatory starting points included the updated Lloyd's Register Guidance Notes and AM service programs [4,5], DNV standards and certification procedures, including DNV-ST-B203 and accompanying service specifications [6,7], as well as the ISO/ASTM 52915 international format for presenting AM models [18]. Industry cases and practical precedents (AML3D accreditation, Keppel certification, and Shell experience) were used to verify their applicability of the regulations under real-world conditions and to assess time and cost effects of implementing AM in ship repair [8, 9, 16]. The empirical substantiation of economic significance was based on estimates of the cost of unplanned downtime and market analyses of spare parts supply for an aging fleet [1,2]. The documentary stage included systematic comparison of LR and DNV requirements for traceability, Build Report, and PQ/MQ requirements, thereby identifying common control points: feedstock traceability, layer parameter recording, heat treatment, and non-destructive testing [4,7].

3. Results and Discussion

The newest versions of regulatory papers are striving for printed parts to be viewed by classification societies as the same as cast and forged products. The LR package is joined by separate rules for certifying powders and wires for WAAM, making it possible to protect the whole chain from feedstock up to assembly drawing and thereby eliminating breaks in traceability [5].

DNV follows the same methodology using the DNV-ST-B203 standard, which by December 2022 had widened its scope to five metallic technologies, among which are DED-Arc, PBF-LB, and Binder Jetting [6]. Qualification procedures are described in service specification DNV-SE-0568, and the accompanying Additive Manufacturing Certification program launched in 2024 offers a unified dossier for materials, processes, and parts, which facilitates interactions with the ship register for yards and spare-part suppliers [7].

A typical qualification route starts with analysis of the digital model and assessment of part criticality; it is followed by production process qualification, including control of printing parameters on experimental cubes, mechanical tests after heat treatment, tomography, and ultrasound. After successfully passing PQ and MQ, the manufacturer receives Approval of Manufacturer. Each production batch is accompanied by a Build Report with digital layer-by-layer records and variable beam energy, which satisfies LR and DNV requirements for build verification [4]. For especially critical elements, which include hatch locking and clamping hardware, a thorough audit of the quality system and selective teardown of finished parts for metallography are mandatory.

Practice confirms the viability of this scheme. In 2022, AML3D became the first in the world to receive DNV accreditation to produce significant marine components using Wire Arc technology, which included qualification of a real steel assembly with fatigue crack-resistance tests [8]. Earlier, Keppel Offshore & Marine certified with LR the production of parts made of ship-grade steels using laser cladding, showing that facility approval and part certification can be completed in six months, given established non-destructive testing methods [9]. The precedents show that the regulatory fabric which LR and DNV interwove between 2023 and 2025 permits putting into service critical hatch parts made at distributed service centers as long as there is adherence to process, material, and batch qualification procedures. Polymer composites—mainly carbon-fiber-reinforced polyamide 12 (PA12-CF) and high-temperature PEKK—printed by selective laser sintering or FFF are already being used for lightweight hatch covers and sealing inserts, where specific strength and corrosion inertness are of importance. Carbon-fiber-reinforced PA12 exhibits an ultimate strength above 85 MPa and water absorption below 0.6% after 30 days in artificial seawater, which is almost ten times lower than unreinforced ABS, thanks to the partially crystalline matrix and the hydrophobic fiber network [10]. SEM images of different fibers after different types of exposure at 55 °C/66 days are illustrated in Figure 1.

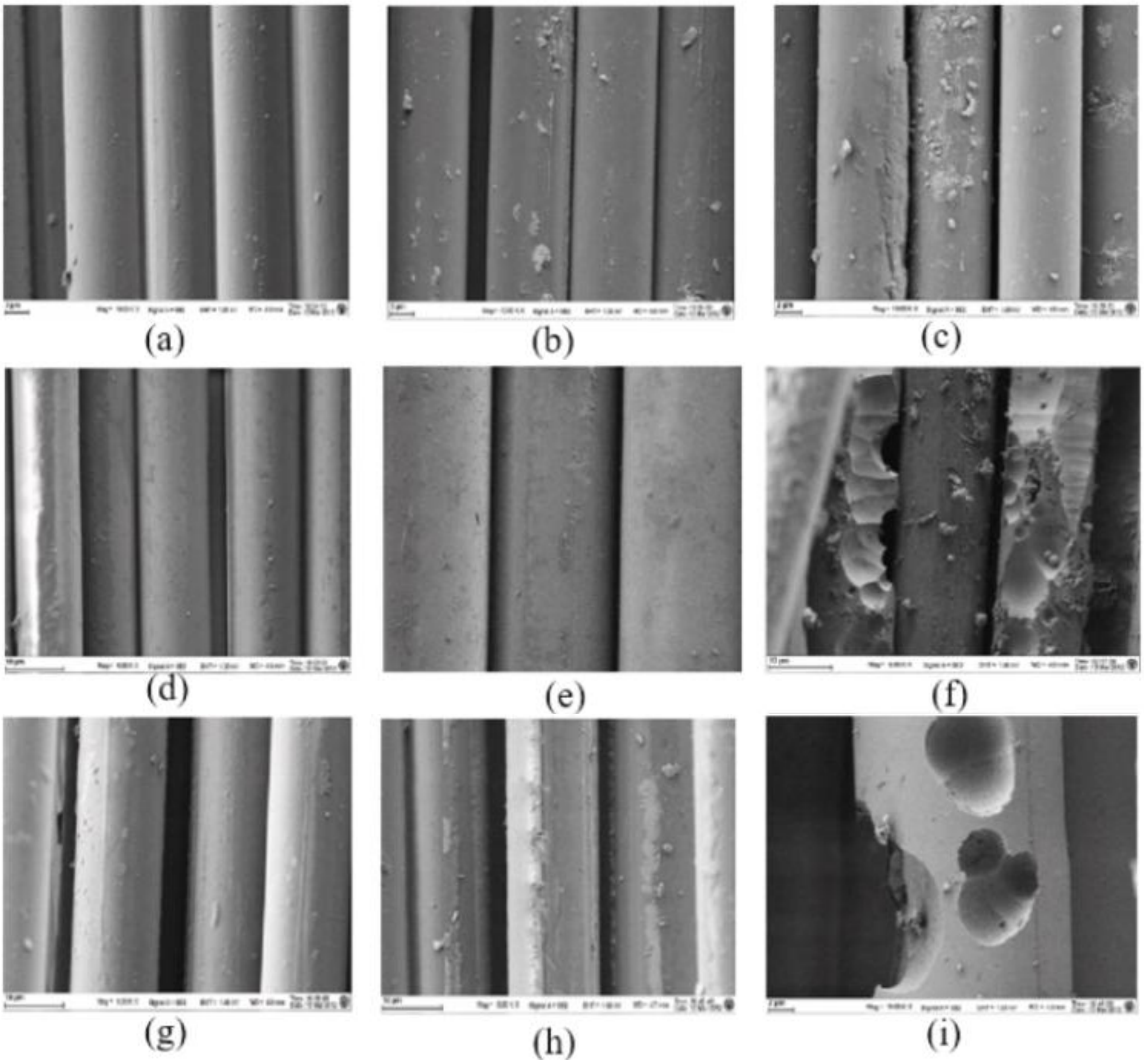

Figure 1: SEM images of different fibers after different types of exposure after 55 °C/66 days. (a) CF/original, (b) CF/salt, (c) CF/alkaline, (d) BF/original, (e) BF/salt, (f) BF/alkaline, (g) GF/original, (h) GF/salt, (i) GF/alkaline [10]

PEKK, extruded at 360 °C, exhibits a glass transition temperature of about 160 °C and maintains greater than 90% retention of flexural strength after exposure to salt fog for 1000 h. This application allows integration with aluminum frames and gasket seating areas [11]. Both systems are in the updated July 2025 "Guidance Notes for Polymer Additive Manufacturing" from Lloyd's Register, where for splash zones a water-absorption limit up to 2% and an elongation at break above 3% are specified — which has been confirmed by tests on coarse specimens on EOS P 810 and Markforged FX20 installations [4].

For locking elements—dogs, pins, and hinges—the industry is transitioning to corrosion-resistant steels fabricated by laser powder bed fusion. Tribocorrosion tests show that LPBF duplex steel specimens lose only 0.9 mg·cm^{-2} over 72 h of sliding in 3.5% NaCl versus 1.4 mg·cm^{-2} for wrought 316L, confirming their suitability for hatch-closing mechanisms operating in saline aerosol [12]. DNV-ST-B203 powder specifications keep nitrogen and sulfur at the level of wrought products, and published articles show that commercial heats stay within these limits with no effect on printability. Post-processing closes the technological chain from porosity and residual stresses [13]. Solution annealing followed by water quenching restores the phase balance of duplex 2205, plus a short aging at 205 °C gives strengthening to maraging steel with no warping. Surface quality remains a functional factor: dogs ground to Ra 0.8 µm show ten times longer resistance to corrosion initiation compared with parts in the as-built state; therefore, Lloyd's Register requires mandatory machining or shot peening of steel spare parts installed in splash zones[14]. In sum, choosing the right polymers or steels and the proper thermal and mechanical finishing ensures that the same regulatory criteria are met, which classification societies set for traditional cast and forged parts, thereby making it possible for additive technologies to speed up the production of spare parts for marine hatches in a reliable way.

The digital preparation chain begins with the accurate capture of the geometry of obsolete hatch parts. Non-contact laser scanning generates a dense point cloud, which is converted into a CAD model in a matter of hours; in this way, manufacturers bypass "bridge purchases" and altogether avoid the risk of buying the wrong nomenclature [15]. Reverse modeling is immediately integrated into the printing process: on a Shell offshore platform, replacing an unavailable OEM cover took two weeks instead of sixteen, and total costs fell by about ninety percent because the entire chain—scanning, parameterization, and fiberglass printing—was executed from a single digital file rather than through mold making [16].

The next step is parametric topology optimization. By applying material distribution algorithms under given loads, researchers achieved a reduction in the mass of test structures by 43–77% while maintaining a static load-bearing capacity of 10 kg; the same method makes it possible to remove up to half of the metal from a hatch latch and thus reduce inertia during closing without taking the component outside certification strength limits [17]. An example of one such structure is shown in Figure 2.

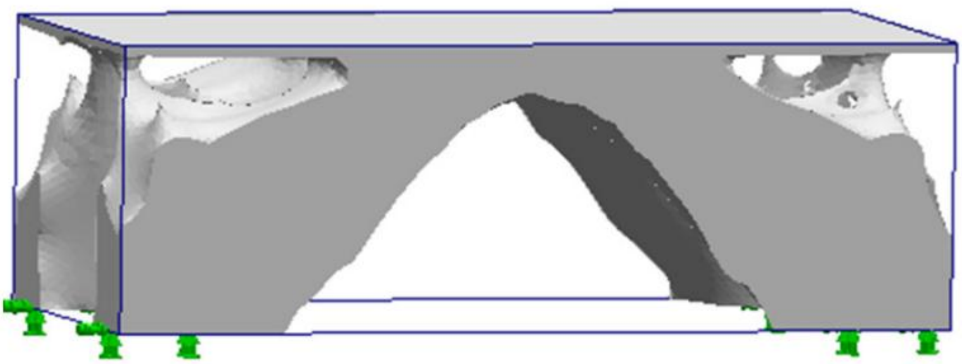

Figure 2: The structure reduces weight by 59% [17]

The resulting models turn into valuable digital assets that require formalized storage and protection. ISO/ASTM 52915 defines the AMF format, which ensures unambiguous representation of geometry and metadata but explicitly notes the absence of built-in integrity control and encryption mechanisms, which shifts the responsibility for cyber-protection to users and service centers [18]. The recommended practice today is to host files in hierarchical "digital warehouses," where each object is linked to versions of printing parameters and quality-control logs. Implementing exactly such a closed loop already allows Shell and other operators to smoothly switch from a physical warehouse to an on-demand system with a global network of qualified printers, eliminating not only delivery delays but also the risk of spreading unauthorized part versions [16].

The economic model of a distributed fleet of additive equipment is based on the sharp drop in unit cost once fixed costs for the printer, process qualification, and energy are spread over a small but regular series. At volumes up to fifty spare parts per year, total costs are comparable to ordering a cast batch at an outside shop, yet they add a key advantage—speed. The printing station remains loaded episodically, so depreciation is allocated more thinly than in a complete industrial cycle, and operators can flexibly convert equipment idle time into savings on logistics and duties.

Inventory stock transforms from metal parts into a set of protected files, which means storage, preservation, and regular inspection costs disappear. Reducing working capital frees up resources of shipping companies, allowing them to be redirected to maintenance or fleet modernization. Most importantly, downtime is minimized: when a latch or hinge is printed right at the yard, the ship receives the part within a single technological window instead of waiting for delivery from another hemisphere. The financial effect manifests itself not in the price of the part itself but in the loss averted from lay-time and schedule disruptions.

Rational logistics in digital form also brings environmental dividends. Ceasing to send heavy metal castings by air lowers the carbon footprint significantly, and lighter parts optimized for topology further reduce fuel use when in use. As files move through safe ways and feedstock is kept on hand, the amount of transport acts drops to a minimum, which blends well with the maritime industry's decarbonization plan, making additive tech not just a money-wise but also a green pick.

Implementation of additive technologies at a ship repair yard begins with an analytical stage: the engineering service compiles a matrix of all hatch assemblies, assesses their impact on safety, failure frequency, and downtime duration, and then ranks items by priority, as shown in Figure 3.

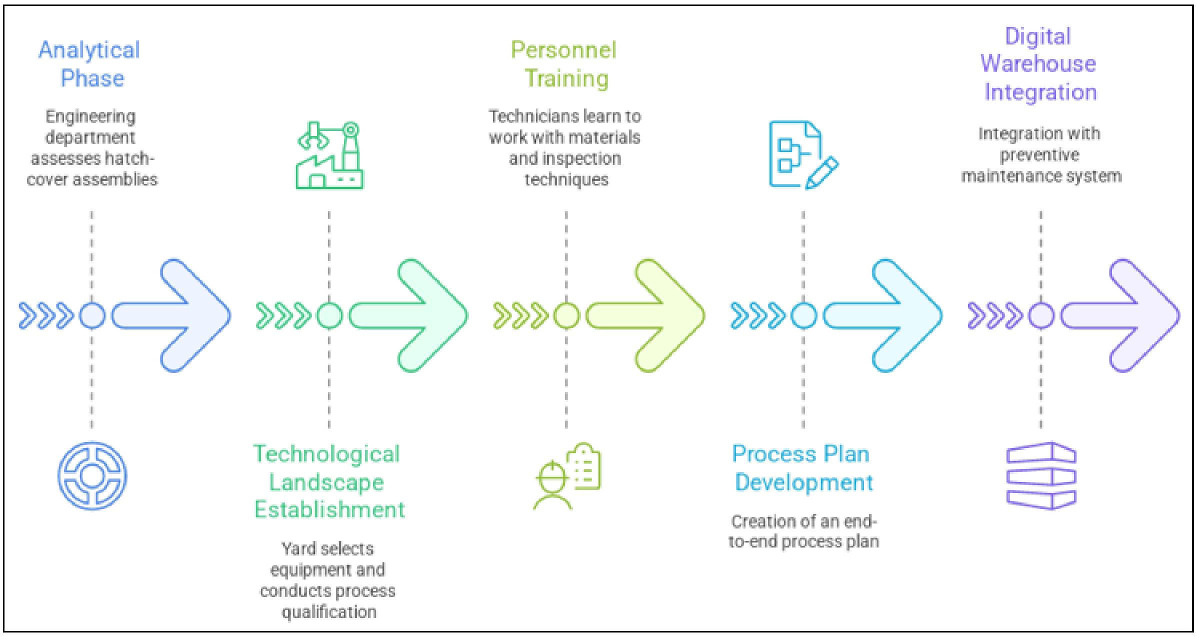

Figure 3: Additive Manufacturing Implementation in Ship Repair (compiled by author)

Such an audit identifies parts whose scarcity is most painful for dry-dock schedules and determines the primary set of digital models that must be converted into printable format. Classification by criticality simultaneously sets requirements for materials, property control, and certification level, preventing resources from being wasted on qualifying low-significance components.

The yard then establishes the technological landscape: it selects equipment for the specified range of geometries and loads, conducts process qualification through printing specimens, mechanical tests, and initial certification, and thereafter formalizes authorization by the classification society. In parallel, a personnel training program is created, where operators learn to work with powders or filaments, and the metrology department masters tomography and ultrasonic flaw detection. The result is an end-to-end process sheet from loading feedstock to final part marking, which minimizes variability between batches and provides a foundation for subsequent certification of each order.

The final step is integrating the digital warehouse with the fleet's planned preventive maintenance system. When a vessel schedules dry-docking, the software matches planned operations with available additive models. If printing is required, prints are triggered beforehand so that parts will be ready by the time the vessel arrives. In this way, the yard helps convert dynamic demand from the fleet into an organized job queue for the printing fleet, which helps in removing sudden shortages and also helps minimize downtime, plus it creates a closed data loop whereby each repair's results enrich the parameter base, thereby improving subsequent forecast accuracy as well as quality stability.

4. Conclusion

Thus, additive technologies deliver practical and realizable acceleration of spare-part production for watertight hatches by transforming physical warehouses into digital catalogs with the ability to fabricate parts directly at the yard or on board. This is only possible if the qualifications and post-processing recognized by the concerned classification societies are applied. Once regulatory updates by LR and DNV have been made and when certification programs for materials and processes exist, then the path from a digital model to an operationally acceptable part is formalized. It means that using AM for locking hardware and hinges is not laboratory work but rather an integrated technological solution.

Polymer composites based on PA12-CF and PEKK have demonstrated strength and corrosion resistance viable for lightweight panels and seals. Metal technologies (LPBF, DED/WAAM, etc.) combined with heat treatment, tomography, and mechanical finishing deliver properties for locking mechanisms comparable to forged or cast parts. Porosity management, phase equilibrium reestablishment in duplex steels, and surface attainment to about Ra 0.8 μm are the most critical since they attack directly at the very core of both corrosion resistance and fatigue reliability.

From an economic and operational perspective, AM brings significant benefits because there would be drastic reductions in delivery time as well as downtime (examples of hull time reduced by ~80%) and local examples of cost reductions by ~90%. It also includes mass and inertia due to topology optimization (mass reduced by dozens of percent while keeping the load-bearing capacity). Lower logistics and warehousing costs are achieved when switching to a distributed fleet of printing stations. Environmental dividends are gained from the reduction of transport operations and lightweight structures.

Practical implementation requires conducting an audit of the criticality of assemblies and hence preparing a prioritized list of digital models, selection and qualification of equipment and materials, process refinement through PQ/MQ and Build Report system, organization of a personnel training program, and integration of the digital warehouse with the planned preventive maintenance system. Adhering to this sequence ensures reproducible quality, reduced downtime, and gradual data accumulation to improve the reliability and economic efficiency of AM deployment in ship repair practice.

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