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D1.1 Document study

AM spare parts in the maritime industry

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1 Introduction

1.1 Objective and methodology

This project note summarizes recent reports and advances in the scientific literature on additive manufacturing (AM) of spare parts, with particular relevance to the maritime industry. The note begins in section 1.1 with a few comments on the adoption of AM across all industries. Section 2 is dedicated to the use of AM in the after sales market. This section is organized in three parts, focusing on 1) the state of the art for AM spare parts in the maritime industry 2) experiences with onboard printing and 3) lessons from AM spare part production in other sectors. The note concludes in section 3 with a short summary of the findings.

The main objective is to provide an update on existing knowledge that can be used as basis for establishing a common level of knowledge between project participants and be useful in future publications from the DAVAMS[1] innovation project. The DAVAMS project supports Wilhelmsen Ships Service in developing a new supply chain for trade in spare parts made by AM across the world. The method used to identify the literature is searching in open online sources by the use of key words related to the topic, and "snowballing" by going through references in identified papers and reports. Grey literature is included because many of the industry-based projects are presented in project reports rather than peer-reviewed journal papers.

For a comprehensive literature review on spare part logistics management in the maritime industry, please consult Mouschoutzi and Ponis (2022). Kunovjanek, Knofius and Reiner (2020) presents a systematic review of the literature on AM spare parts where they identify 141 relevant articles (of which none covers the maritime industry).

1.2 Global AM adoption and its impact on international trade

In a recently published white paper, the World Economic Forum assesses the current state and future of AM at the industrial scale (Betti, Seidel and Meboldt, 2022). The report is aimed at manufacturers and industrial end users. It lists the potential challenges to AM adoption under three main headlines: technology-related, organizational, and ecosystem-related. Results from a limited survey and interviews with industry and policy actors show that high production and post-processing costs is the most important barrier to more widespread adoption of AM: “Today and in the foreseeable future, the production costs of AM parts are a principal obstacle to adopting AM.”

Another barrier is the lack of defined standards in regulated areas, such as aerospace. And finally, lack of skills and know-how is a barrier, both on a company and society level. The report highlights three characteristics of highly advanced AM applications that have been commercialized: a) exploitation of the digital process chain, b) qualified, flexible supply chain networks, and c) novel AM materials. It also lists what they see as the best practices for adoption of AM: a) implement in iterations, b) pull, don’t push, c) collaborate to complement, d) strategize and support. It's a good overall report on barriers and drivers for implementation of AM, and a reference point for how major economic actors evaluate what needs to be done to strengthen

[1] Full project name: Disrupting and Adding Value to maritime supply chains by using Additively Manufactured Spare parts. A project presentation is available at: https://www.sintef.no/en/projects/2022/davams-disrupting-and-adding-value-to-maritime-supply-chains-by-using-additively-manufactured-spare-parts/

the diffusion of AM. It does not address the maritime sector specifically, but the conclusions and discussions are highly relevant for the sector.

The OECD Trade and Agriculture Directorate has published a report on the impact of AM on international trade (Andrenelli and González, 2021). One motivation for the report is a concern among customs authorities that AM can replace international trade in the future. They analyze the relationship between international trade in 3D-printer machines and trade in printable objects by the use of proxy indicators. For example, a sample set of 10 000 models from the Thingiverse repository is used to estimate the kind of items that are printed in a home and hobbyist setting. The 2022 revision of the Harmonized System nomenclature of the World Customs Organization contains a new code, *Heading 84.85 – Machines for additive manufacturing*, but at the time of writing this code was not yet implemented. The way AM is used (centralized or decentralized production) and the original origin of items that are printed (domestic or foreign) will influence whether AM is *trade enhancing* or *trade substituting*. Trade in feedstock materials and design services are part of the impact considered.

The data show that trade in high-tech printable goods, such as aircraft parts and orthopedic appliances is growing approximately as fast as total trade. Their econometric analysis shows a positive and statistically significant relationship between proxy measures of imports of 3D printers and exports and imports of 3D printable products. This indicates that AM is unlikely to have been replacing trade in the past. There is no indication that AM will have wide-ranging impacts on physical trade in the short to medium term, and therefore there is no immediate need to renew trade tariffs and customs duties on electronic transmissions.

2 AM in spare parts production in the maritime industry

2.1 State of the art for AM based supply chains

Shipping is characterized by operating capital-intensive assets and by heavy utilization of equipment in a highly corrosive environment, totally dependent on a well-functioning maintenance organization to ensure safe operations. Unexpected downtimes of maritime assets lead to a significant loss of revenue and can also cause safety consequences. A particular challenge is that the assets are constantly changing locations so that the expediting of spare parts can be hard to plan for. The optimal logistic maintenance models for supplying conventional spare parts are still subject to study (e.g., Eruguz, Tan and van Houtum, 2018). An earlier study by Turan *et al.* (2009) found that the contribution of maintenance and service logistics to the operating costs of maritime vessels can be as high as 25 to 35%.

Ziółkowski and Dyl (2020) reviews the literature on the use of AM in shipbuilding, including the production of spare parts. They identify a number of use cases that vary substantially in the materials, AM technologies, and applications used. They point to risk aversion as an important barrier to switching between production systems. The involvement of classification societies and standardization of production is seen as important to meet this challenge. Onshore metal printing (DMLS, EBM, WAAM and binder jetting) is seen as the most promising approach to producing on-demand spare parts, but high costs and the need for quality tests are issues that need to be solved. FDM machines that print composite materials is seen as a low-cost alternative that can be utilized onboard, eg. installed in an engine room, for non-critical parts.

The identified use cases are primarily simple parts that are not safety-critical. But the attention of large companies makes the authors optimistic that AM production will soon be applied to critical areas (propellers, engine parts, etc.). The identified advantages of AM are summarized in Figure 1.

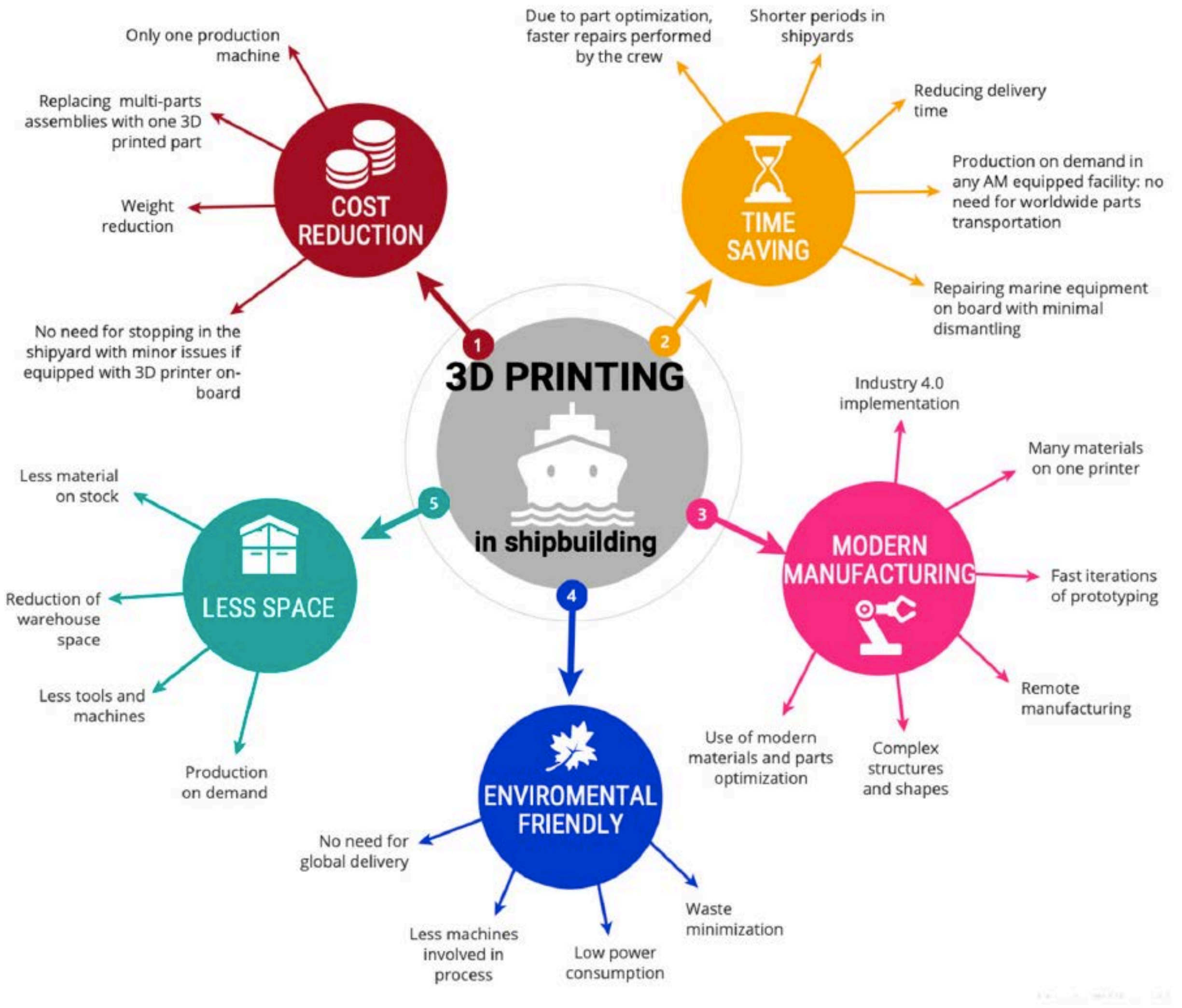

Figure 1 Advantages of 3D-printing in shipbuilding[2]

Kostidi, Nikitakos and Progoulakis (2021) investigate the benefits to end-users of introducing AM in the supply chain for maritime spare parts. Questionnaires were collected from 140 (out of 200 invitations) participants, categorized as "crew engine", "crew bridge", "technical", "purchasing", "ship owners/CEOs" and "other (R&D, training, academic)". A majority (approx. 16/30) of the shipowners/CEOs answered "yes" to the question *Is your company thinking of/examining the use of 3D printing?* 12 answered "no" and 4 answered "I do not know" or "not yet". The expectations for cost reduction were highest among the Shipowners/CEOs and Other (R&D, etc.) categories and lowest for Crew engine and Technical, but almost all responders expected at least "medium" cost reductions". Expected reductions to storage space were low to medium. Part quality assurance is clearly identified as the main barrier.

[2] Source: Ziółkowski and Dyl (2020).

In a related conference paper, Kostidi *et al.* (2022) extends the stakeholder views by also including upstream actors (original equipment manufacturers, subcontractors, regional or local distributors, suppliers, traders). Questionnaires were sent to 200 participants, of which 180 replied. A key result is that suppliers are much more optimistic about the expected impact than end-users. This is true for all of the three areas that were considered: cost reductions, service improvement and storage space reduction. The modal answer from suppliers were "Very high" expected impact, which is the most positive option available. In terms of barriers, the main barriers according to suppliers are intellectual property rights and access to digital files.

Singapore is a large shipping hub and have invested heavily in a national policy to master advanced manufacturing. This combination has made the country a testbed for developing new supply chains and business models for AM spare parts to the maritime industry. A feasibility study was conducted in 2018-2019, led by DNV, where several ship owners came together to identify promising parts that should be both technically and economically viable to print. A set of 100 parts were identified from a database of nearly 600 thousand marine parts orders. The 100 parts were classified as either a) highly feasible to print without class certification, b) highly feasible to print with class certification, and c) not feasible for 3D printing. The results of the feasibility study are summarized by Kandukuri (2019).

Building on this experience, the Singaporean government launched a second round of projects, called joint industry project (JIP) phase 2. This time the focus was on printing and installing components, and six consortia consisting of ship owners, print service providers, and classification societies were included. A presentation of the consortia and the way that the project is facilitated by NAMIC,[3] MPA[4] and SSA[5] is presented in a landscape report on AM (Maritime Singapore, 2022). Some examples of parts that are chosen as use cases are fuel oil pump shaft, pump and valve parts, cooling water pipe and connectors. The parts are reverse engineered and printed onshore in metal alloys. A third phase is expected to be launched in 2023 where the focus is likely to be shifted towards classification, quality testing and insurance.

2.2 Experiences with onboard printing and AM spare parts as temporary replacements

The most extreme case of localized production of spare parts is printing parts onboard a vessel. This was experimented with during the Green Ship of the Future project, funded by the Danish Maritime Fund (Elsborg-Jensen, 2018). Nine FDM printers were installed on six ships and three rigs. The printers were considered to be minimum viable solutions for onboard printing. Over three years, crew members printed a few non-critical items, such as knobs and handrail brackets. However, the usage did not meet expectations. It appeared that crew members may not have been sufficiently interested to fully embrace the potential. A key insight is that "it must be as simple to 3D print a spare part onboard, as it currently is to order it." Although the FDM printers were cheap relative to the cost of metal printers, the costs were deemed too high for installing printers onboard every vessel.

The project faced issues with IP-rights, with no OEMs willing or able to provide original files for printing. In terms of repairs and refurbishment, two turbine blades were printed using laser

[3] National Additive Manufacturing Innovation Cluster.
[4] Maritime and Port Authority of Singapore
[5] Singapore Shipping Association

cladding technology. The parameter optimization was difficult and time consuming, and the final result did not have sufficient quality for operational testing. The mode of transportation is the key factor that will determine whether repair or replacement of the part is most sustainable. In conclusion, it is clear that the human factor (skills, interests and know-how) is crucial to the success of onboard AM spare part production.

The experience from Green Ship of the Future favors onshore production. This is in line with Holmström *et al.* (2010) who comments briefly on the potential deployment of AM used as "mobile rapid manufacturing". They advise against it since current AM machines were not constructed for use in mobile environments. Similar concerns are raised by Ziółkowski and Dyl (2020) who state that “on board the ship there is practically permanent rocking and vibration, the temperature changes dramatically depending on the season, time of day or geographic region. All these factors can negatively affect print quality.”

Some other authors also make a point of AM spare parts being of lower quality than conventional parts and consider the primary function of AM spare parts to be temporary fixes until a replacement part can be obtained. This is the case in the models of Westerweel *et al.* (2021) and Knofius, van der Heijden and Zijm (2017). Onboard printing could be an example where AM is used for making temporary fixes, but the practical relevancy of this remains to be proved empirically. A related lesson from the Green Ships of the Future is that "AM may be 'good enough' until the new component arrives, but a major challenge here is the classification societies and their reluctance to recognize and approve repairs."

2.3 Additive manufacturing of spare parts in other sectors

The idea of using AM technology in the maritime industry is far from new, but the diffusion of the technology has been slow. This is not uncommon for large scale digital transformations Vogelsang et al. (2019). Osmundsen, Iden and Bygstad (2018) propose that companies aiming to succeed with a digital transformation should focus on a supportive and agile organizational culture, well-managed activities, engaged managers and employees, and leveraged external and internal knowledge. To understand how the digital transformation of AM can take place in the marine industry, it is illustrative to examine similar shifts in other industries, such as aerospace, energy production, and defence.

Holmström et al. (2010) studies the effects of different models for introducing AM in the spare parts supply chain for the aviation industry. They conclude that the technology is well suited for on demand and centralized production of spare parts and that this model is the most likely to succeed. For AM to be applicable in decentralized manufacturing, the equipment should be flexible enough to enable general purpose manufacturing and not specialized, and the availability of such pooled resources must be managed satisfactorily. Building on this insight, Khajavi, Partanen and Holmström (2014) uses scenario modelling of the supply chain in aeronautics to compare operating and downtime cost with AM compared to traditional production. They conclude that AM production led to a reduction in both inventory cost and spare parts transportation costs compared to traditional production. They also conclude that centralized production is clearly the preferable supply chain in their case example. In a more recent work, Khajavi *et al.* (2018) quantitatively examine the feasibility of different AM-enabled spare parts supply chain configurations, using cost data extracted from a case study. These results show that hub-production can provide economic efficiency and reduce equipment downtime.

Ratnayake (2018) describes how digitalized and localized supply chains enable the reduction of delivery lead-times in remote locations and can potentially reduce the bulk of today's spare parts related challenges in the offshore oil industry. The ecosystem for the offshore petroleum industry is modelled as consisting of four main stakeholders: the asset owners, engineering contractors, medium scale manufacturing firms and small-scale manufacturing firms. The latter two are often tasked with producing replacements for obsolete parts that can have complex geometries and where only a few units are needed. The remote locations of offshore installations is another key argument for transitioning to a digital and localized supply chain enabled by AM.

Ratnayake ends the article with a procedure to determine production parameters for AM production in cases where it's not provided by the equipment supplier. And in Abbaszadeh et al. (2022) Ratnayake also presents a procedure for risk-based qualification of AM components to be installed in oil and gas industrial applications. A qualitative case study of the industrialization of AM in the Norwegian oil and gas industry is provided by Johannessen and de Lange (2019). In their master's thesis, they interview six manufacturing firms that supply Equinor with components. Although they have metal AM machines and provide Equinor with pilot cases, AM constitutes a marginal part of their business activities. The transition to AM production is not seen as very disruptive to their organization, and they need to see an economic incentive to change. IP-rights for parts (even obsolete parts) need to be sorted out. The authors conclude that new business models are needed where Equinor shares the risk of transitioning by compensating suppliers adequately financially or state that AM is a preferred production method in tenders

Westerweel et al. (2021) studies the potential for on-site printing of spare parts at remote geographic locations by modelling a dual sourcing supply chain with an AM-based production option. In their model, parts can be supplied from local inventories that are replenished periodically, or parts can be either printed on demand or supplied by express expediting from a central location. Each option has unique costs and trade-offs associated with them. The model is then applied numerically to a use case based on a UN peacekeeping mission to Mali. Here they find a reduction in operating costs of 47% across 14 components of three mission-critical systems, specifically through large reductions (72%) in inventory storage space. They conclude that "on-site general-purpose additive manufacturing (AM) technology, as a temporary solution to shortages, leads to large operational cost savings through on-site inventory reductions and increased asset availability." The printing option is typically used near the end of an order cycle, which is when most shortages occur.

3 Conclusion

The literature presented in this note covers both applied research and more theoretically oriented work. From the use cases and experiences described in the articles and reports, it is clear that additive manufacturing of spare parts to the maritime industry is still in its early stages.

The findings confirm the main message of Halvorsen and Lamvik (2021), i.e. that there are still a number of important barriers that need to be overcome for AM to live up to the expectations of end-users, technology providers and OEMs. These are both technological, organizational, educational, economic, and legal in nature. At the same time, the results point to a great willingness to work to overcome these challenges. Applications in the heavily regulated aerospace industry serve as proof-of-concept and show that viable solutions exist. And the work that is done so far in the maritime industry is a testament to the willingness to come together and seek holistic solutions that include every step in the value chain.

It's also important to remember the important steps that have been taken already. There is now a better understanding of the limits to onboard printing, and the need for general purpose AM equipment that can serve multiple industries and applications. Shipping hubs, such as Singapore and Rotterdam harbors, have embraced their role as facilitators in the digital transformation, and classification societies are increasingly developing their services to the emerging AM business ecosystem.

The reference list should not be considered as a comprehensive list of the relevant literature. The potential exists that important work has been overlooked – in particular studies published in books. Despite this, it is our hope that readers who are new to the topic will find useful sources for further information.

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