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Research Article

Stakeholders' perceptions on the introduction of additive manufacturing (AM) in the maritime spare parts supply chain

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Abstract

Spare parts supply chain (SPSC) plays a crucial role in keeping ship machinery running. This study, rooted in a thorough literature review encompassing both academic and industry research, as well as established standards, seeks to shed light on stakeholder perspectives regarding the integration of Additive Manufacturing (AM) into the maritime spare parts supply chain (SPSC). The aim is to address fundamental questions critical to shaping the maritime spare parts supply chain with AM. The research employs a questionnaire-based methodology, deemed the most appropriate tool for capturing stakeholder perspectives, motivations, and concerns. Participants are categorized as “end-users” and “suppliers” of spare parts. The end-users in the maritime SPSC encompass individuals both on board vessels and in onshore offices, ranging from ship owners to engineers, surveyors, and staff in various departments. On the upstream side of the SPSC, the study engages with manufacturers and suppliers of spare parts, including original equipment manufacturers and third-party subcontractors, as well as various types of distributors and service providers. The research concludes with a comprehensive understanding of the maritime industry’s engagement with AM, balancing cost-efficiency with the preservation of service quality and operational readiness. It identifies significant barriers, such as quality assurance, the need for skills and knowledge, digital asset management, copyright protection, and equipment availability and costs. This study marks a pioneering exploration of stakeholder perspectives within the maritime SPSC concerning the integration of AM technology. It underscores the industry’s eagerness to embrace digital transformation while highlighting key challenges that must be addressed for a successful transition; this is clearly an added value from a practical perspective. As the maritime sector stands at the precipice of technological evolution, understanding these perspectives is integral to steering towards a more efficient, cost-effective, and sustainable future.

1. Introduction

In the course of human history, shipping activities have always been vital for supporting trade. It is also true that, at any point of time, the building characteristics and equipment of a ship are heavily reliant on the vessel’s “intended” mission, and most importantly, upon the technology applications available to support these quite complex activities (Joseph & Dalaklis, 2021). There is also a need to factor in that the maritime transport industry is characterised by the heavy utilisation of equipment

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and machinery under harsh and corrosive operating conditions, which makes maintenance requirements particularly critical due to the detrimental financial and safety consequences of downtime. Consequently, the spare parts supply chain (SPSC) plays an essential role in keeping maritime assets operating efficiently and safely. Transporting goods and/or passengers means operating away from the shoreline and, in many cases, on random paths, presenting additional difficulties in being supplied with the necessary spare parts to permit “normal” ship operability. The shipping cost in several cases (i.e., when a ship is located in isolated or difficult to reach areas) may be higher than the purchasing values of the part itself, in addition to the potential downtime cost.

Wider SPSC management is far more complex than the inventory of the final products due to the unique characteristics of the spare part (Deloitte Consulting, 2013). A spare part's life cycle is longer than the product it goes with, and related demand is very often volatile and unpredictable. At the same time, spare parts providers (manufacturers, suppliers, distributors) strive to maintain a high level of customer service, while minimising related inventory costs. Spare parts availability at the point of consumption makes inventory necessary so that suppliers can respond quickly to demand. On the other hand, keeping an inventory of spare parts causes maritime companies and parts suppliers a financial burden, mainly in capital cost expenditure and logistical storage. In the case of a vessel, the spare parts management problem is different, as the demand point is not stationary. This means that the problem parameter values depend on the location of the demand point at a given time. Eruguz et al. (2018) have shown (with a case study from the shipping sector) that cost savings resulting from a comprehensive optimisation of spare parts stocks and spare parts replacement decisions are significant.

The so-called “Fourth Industrial Revolution”, also termed “Industry 4.0” in the wider literature, is associated with several cutting-edge technologies. Indicative examples in this category are advanced applications like Artificial Intelligence (AI), Big Data Analytics (BDA), Cloud Computing, and Internet of Things (IoT); another important digital tool, Additive Manufacturing (AM), must also be included in the same portfolio, and has the potential to facilitate the transitioning of the maritime transport industry into a new operations paradigm (Ichimura et al., 2022). Kantaros et al. (2023) highlight the growing importance and wide-ranging applications of 3D and 4D printing, particularly in the context of Industry 4.0 and across multiple industries. In any case, AM- also very broadly known as 3D printing (3-Dimensional Printing)- is transforming how products are designed, produced, and serviced. 3D scanning, 3D printing, and CAD design software are considered important tools in Industry 4.0 product development processes (Kantaros, Soulis, et al., 2023). Industry 4.0 is characterized by a confluence of novel technologies that are radically transforming various industries, the global economy, and our way of life (Tsaramirsis et al., 2022).

AM is clearly a very innovative technology that brings new opportunities and benefits to the SPSC. The specific methodology enables distributed manufacturing in small batches, thus minimizing the inventory and reducing delays and costs. It is based on the construction in layers by directly converting the 3D data into physical objects (Technologies & Terminology, 2012). AM enables on-demand production without dedicated equipment or tooling, unlocks the full potential of digital design tools, and can offer breakthrough performance and unparalleled flexibility. Based on the fact that AM provides the ability to manufacture finished components in a decentralized manner, certain researchers strongly argue in favor of digitizing spare parts and of their decentralized construction (Chekurov et al., 2018; Knofius, 2020). Many problems faced by the industry today can be solved by the aforementioned technologies (3D printing, 3D scanning) (Ganetsos et al., 2023).

The maritime transport industry, and especially those vessels travelling in remote areas, should not to be left out from this extremely beneficial technology application. Top global marine propulsion engine vendors, motivated by the benefits of AM, have already experimented with this new technology, not only in prototyping but also in their “standard” production process. Initiatives such as “Pilot Project 3D printing of Marine Spares” (Final Report Pilot Project 3D Printing of Marine Spares, 2016; Green Ship of the Future, 2017) and “Maritime and Port Authority of Singapore”

(Kandukuri, 2019) aimed to explore the practical use of AM. As an emblematic example, spare part blades have been built by a “wire arc additive manufacturing” process for the propeller of the French Navy mine hunter “Andromède” (Nota et al., 2023). New materials and production methods explored by academic research set innovative routes, such as applying fiber-reinforced composite materials in the marine environment; such recent advances in this area were presented by Rubino et al. (2020). Although there are several studies (Holmström et al., 2010; Khajavi et al., 2014; Liu et al., 2014; Li et al., 2017; Walter et al., 2004) on the implementation of AM technology in areas similar to the maritime industry (with moving assets or isolated environments), studies specifically on the maritime industry are, for the time being, rather scarce. Maritime transport is the backbone of world commerce; however, its digitalization lags significantly behind when we consider some basic facts (Sanchez-Gonzalez et al., 2019).

Although necessary for world trade due to its smaller size, shipping has not received significant interest in the SPSC. It is understood that any lessons learned from the introduction of new technology, before application, should take into account the specific characteristics of the industry in which it is to be applied (in this case, the maritime one). The purchasing process is pretty much typical, although one must note that a ship can be away from the base, and changes location, so that a spare must be delivered to the next port that the ship will reach within a specific time window (Kostidi & Nikitakos, 2018).

This work extends previous work (Kostidi et al., 2021) that presented the end-user views (onboard the vessel and at the land office) upstream (original equipment manufacturers, subcontractors, regional or local distributors, suppliers, traders). By capturing the stakeholders' views and expectations along the whole SPSC (starting from the maker of the part and including, of course, the end-user), this paper aims to assess the industry's readiness to accept this new digital technology application and identify the most influential factors for its successful implementation. Following this brief introduction, the remainder of the paper is structured as follows: first, the literature review is presented, with the aim to formulate/explain the related questionnaire that was used for data collection purposes. Then, a more detailed explanation of the methodology follows. Next, the collected views of the involved stakeholders of the SPSC are analyzed, and the results are presented. Finally, results are discussed, and conclusions are drawn.

2. Literature review

The wider maritime transport industry, which comprises shipping companies and related vessels, ships manufacturing companies, and various entities ashore (like ship management entities, port authorities, etc.) has slowly begun to undergo a digital transformation, with the issue of AM included in the relevant discussions. Although AM utilisation is presently in its infancy, once it becomes economically viable for mass production, it could revolutionize the SPSC. An extensive literature review was undertaken to identify qualified academic and industry research and standards that could assist in the formulation of the necessary survey questionnaire.

2.1. Main positive effects of Additive Manufacturing and the spare part supply chain

The motives to introduce new technology applications (and especially those that rely heavily on digital means) vary considerably by industry. In aerospace, components need to be geometrically optimised to result in lighter structures and thus reduce aircraft weight and fuel consumption. In the automotive industry, a significant motive is the rapid creation of prototypes and tools and the supply of spare parts for old vehicles. These incentives lead to research in the aerospace and automotive industries to exploit the potential of new technology. As AM matures in the maritime transport industry, specific incentives will emerge. Meanwhile, as the supply of spare parts is vital for vessel maintenance, the maritime industry can take advantage and implement lessons learned from studies already conducted in other industrial sectors. The main positive effects of the application of AM in the SPSC in the area of moving assets, as stated by authors in the literature, are asset availability

(Khajavi et al., 2018), economic efficiency (Li et al., 2017; Westerweel et al., 2018), reduced inventory (Holmström et al., 2010; Liu et al., 2014; Ghadge et al., 2018), improved service (Holmström et al., 2010; Khajavi et al., 2014; Ghadge et al., 2018), lead time reduction (Ratnayake, 2016), better supply chain performance (Delic and Eyers, 2020), and decreasing carbon emissions (Li et al., 2017; Ghadge et al., 2018). Company objectives lead company decisions and concentrate efforts in obtaining them. The SPSC in the maritime industry involves many stakeholders whose objectives may differ, so any exploration of the potential of AM improvements should start with noting the objectives of each stakeholder.

2.2. Barriers toward the introduction of Additive Manufacturing

All changes (especially technology related ones) encounter obstacles, and these must be appropriately mitigated. Knowing the expected obstacles when a part is made by 3D printing will help for better preparation and necessary risk mitigation. The various barriers towards enterprises' digitalisation in manufacturing can be grouped into individual, organisational, environmental, and technical ones (Vogelsang et al., 2019). In addition, barriers such as standardisation, quality assurance, intellectual property rights protection, and cyber security (Gupta et al., 2020) legacy of non-digitalised product and component information must be further investigated (Osborn, 2016). Among significant technical barriers, the low number of usable materials, insufficient accuracy levels, tolerances, and build chamber size limitation (Kretzschmar et al., 2018) must also be overcome. Another significant barrier is that the industrial design methodologies applied are more appropriate for "traditional manufacturing" purposes, and do not consider the capabilities of AM. Furthermore, the necessary computer-aided-design (CAD) files often do not exist, and technical drawings can be difficult to locate (Ballardini et al., 2018).

The need to ensure the functionality and compatibility of products and consumer safety is addressed by already published, and a certain number of upcoming, technical standards (IEEE, 2011). Certification and quality assurance are required to give confidence to all interested parties that a product, process, or service fulfils specified requirements (ISO/IEC 17065:2012(en), 2012). Small batch production, or the customisation of products by AM, requires new quality assurance (i.e., non-destructive) and certification methods to produce procedures and products. This need could be covered with published guidance notes by classification and certification societies, such as Lloyd's Register and TWI (The Welding Institute), (Lloyd's Register and TWI, 2017), DNV (Det Norske Veritas) (DNV GL, 2020), and ABS (American Bureau of Shipping), (ABS, 2018), Bureau Veritas Marine & Offshore (Bureau Veritas Marine & Offshore, 2019). AM can truly revolutionise the industrial landscape, and these changes require new engineering and management skills to exploit fully and sustainably the benefits offered by these advanced technologies. However, new technologies create a lack of talent, an "additional" need for training in specialisations, and a workforce adaptable to change (Despeisse & Minshall, 2017). Therefore, it would be helpful in the preparation of the introduction of AM in the SPSC to have a picture of how the stakeholders view the most frequently met barriers in literature, such as technical know-how, staff skills equipment (printer) cost, material availability and cost, quality assurance, and intellectual property rights protection.

2.3. Suitable spare parts for Additive Manufacturing

Characteristics of suitable spare parts, as proposed from initiatives in the area of the maritime industry (Final Report Pilot Project 3D Printing of Marine Spares, 2016; Kandukuri, 2019), provide a picture of the parts that may have the potential for 3D printing. The comprehensive list of 100 parts (such as worm gear, bearing shell, nozzle ring, compressor housing, et al.) derived by a Joint Industry Project (Kandukuri, 2019) can provide a good starting point. Parts that are (Final Report Pilot Project 3D Printing of Marine Spares, 2016) infrequently demanded (e.g., space ring Huisman, eccentric reducer, open spelter socket) must be available in the case they are needed, especially ones that are of high supply risk (hinge fokker), so they must be in inventory. Parts ordered in small quantities

(turbocharger nozzle ring) usually have quite an expensive overhead cost. Keeping high-value parts in inventory means tied-up capital. If parts are of high design complexity, they are difficult to be made otherwise (e.g., in a lathe), or they are made up of many components that require assembly. For practical reasons, the chosen parts must be of such a size that can fit in the process chamber.

2.4. Availability of information

Spare parts construction near the end-user presupposes the existence of the required information for its construction, such as detailed construction plans, construction material, etc. It is well-known that manufacturers secure a portion of their profits (perhaps the largest) from spare parts sales. Moreover, proper maintenance and the use of genuine spare parts by the users of their machines is required to maintain the warranty. For these reasons, but also to protect themselves from imitations, they are protective of the technical information they provide, limiting it to what is absolutely necessary

3. Methodology

The previous review indicated that the following questions should be investigated further:

- What are the benefits of AM's introduction in the SPSC in this industry?
- What are the factors influencing the application of AM in the SPSC?
- What spare parts are (the most) suitable for AM?
- What information is available for manufacturing spares?

The research is not aiming at specific AM technology (FDM-type additive manufacturing with plastic, Powder Bed Fusion, Direct Metal Laser Sintering, etc.), but AM in general. The questionnaire method was selected, since it was viewed as the most appropriate tool to capture the involved stakeholders' perceptions and understand their related motives and fears. The selected interviewees were grouped as "end-users" and "suppliers" of the spare parts. Although there are more strategic/top management equally important issues associated with AM (e.g., longer life of assets, or better use of capacity), the issues examined in this paper were chosen to be the same for all the stakeholders for comparison reasons. The following interview protocol was followed for the data collection: Initially, the participants of the questionnaire were informed about the purpose of the research, and were asked to explain/clarify their position in the SPSC (i.e., people on board ship or shore offices: ship owners, surveyors, engineers, etc. (for group A), and stakeholders along the path from production to end user (group B)). In order to effectively screen the responding participants, a reply by email was requested. The questions asked were structured in sections, either as multiple choice or as scale 1 to 5. The data collected through the two types of questionnaires were analyzed for reliability and validity. Since the number of the respondents from each position was different, care was taken for comparison within the same group of stakeholders, or position.

The end users' group of the SPSC involved: people on board a vessel (bridge and engine crew) and in an ashore office (ship owners or chief executive officers (CEO); staff in technical, procurement, training, research and development (R&D) departments). Most of them had absolutely no, or very limited, AM knowledge, so a short presentation of the basics of AM took place in the form of "initial familiarisation". The shipping companies visited for interviews were not restricted to a particular type of vessel. The term "3D Printing" was used instead of "Additive Manufacturing" throughout the interviews because it was more understandable by survey participants due to its use in the media. The SPSC upstream group that supplies the parts involved the makers of the spare parts and the suppliers for the spare parts to reach the end-users. The makers could be original equipment manufacturers or third-party spare parts subcontractors. The distributors of the part were central, regional, or local, but could also just be offering services without inventory.

In order to formulate the questions, preliminary meetings were arranged with representative people of all the previously mentioned groups. The top management (ship owners, CEOs, head of departments either technical or purchasing) in companies that showed interest in the subject during

workshops or open presentations were approached first. During these meetings, each lasting approximately an hour, the available technology, capability, and benefits to the SPSC were presented. Furthermore, meeting participants' scepticism was captured, with the aim to record the challenges that such a change would face. The preliminary meetings provided the authors of this paper with a preliminary idea of how to structure the questionnaire. In order to fulfil the research objective and effectively answer the research questions, a series of questions were posed to stakeholders along the spare parts supply chain. The questions of the first part concerned demographic characteristics, such as: gender, age, position in the company, main activity. Respondents were then asked to rank the company's (spare parts-related) goals, such as: cost reductions, improved service, reduced storage space, or any other set by the company.

One set of questions was about using or intending to use 3D printing, barriers they expect to face, and suggesting the best place in the supply chain to install a 3D printing system. The participants could also suggest parts suitable for 3D printing, available information about making the parts, and ways to find suitable parts. The goals of the shipping company guide its decisions and focus its efforts on their fulfilment. The spare parts supply chain in the shipping industry involves many stakeholders. The goals of each of them may differ, so any exploration of the potential for improvements in AM should begin by identifying the goals of each stakeholder. The interview questions were mostly closed (multiple choice, or ranked), but it was possible for the respondents to express their point of view (i.e., suggest spares with high potential to be made by AM). In order to obtain as many views as possible, two well-known marine exhibitions (Posidonia 2016, Posidonia 2018, and SMM 2018) were selected, because they attracted all the targeted stakeholders. In addition, the views of academics were recorded at relevant scientific conferences. The questionnaires were completed either by personal communication, but mostly after an in person talk, by sending a reminding e-mail with the link. Care was taken to make the questions self-explanatory, mainly multiple-choice, and allow the respondent to add comments. In addition, the invitation message contained a link to a presentation that briefly explained the technology. The targeted number of the survey questionnaires for each of the two groups was 200, but some of them, although kind enough to contribute to a free talk, did not complete the questionnaire to the end. The process of conducting the survey lasted a whole year (2018); there then followed the processing of the questionnaires.

4. Research results analysis

The total number of survey questionnaires that was collected from the first group (under the type "end-users") was 140. The target number was 200 (participation response 70 %), but several targeted responders did not complete the questionnaire to the end; however, a few of them were kind enough to contribute to a free talk/informal discussion.

In terms of age range for the 140 respondents (of the end-user group), the 56 or older age group was 36, with 26 %, the 36 - 55 age group was 75, with 53 %, the 26 - 35 age group was 24, with 17 %, and the 25 or younger was 5, with 4 % (**Table 1**).

Table 1 Responders by age in the end-user group.

Age Group	Respondents	(%)
56 or older	36	26
36 - 55	75	53
26 - 35	24	17
25 or younger	5	4
All ages	140	100 %

The highest number of participants was in the 36 - 55 age group, indicating a very mature population that could provide very representative results and recommendations for research.

The role in the company of the respondent was noted as: engine crew- 19, with 13 %, bridge crew- 14, with 10 %, technical department-33, with 24 %, procurement- 32, with 23 %,ship-owners/managing directors (senior managers)- 32, with 23 %, and other group respondents (R&D, etc.)- 10, with 7 %. Most of the respondents work in the shipping company technical departments, while the procurement departments and the shipowners / managing directors (senior managers) follow, with the same number of participants and the same percentage. It should be noted that the majority of survey participants were male (83 %), as the male population is higher by far than the female population in the maritime industry.

The questionnaires collected from the second group (called suppliers) were 182 out of 200 (participation response 91 %). Again, the participants were grouped as business, technical, owners/CEOs, and others (R&D, training, academic). The response from the second group was much better than the first one and is presented by age in **Table 2**.

Table 2 Responders by age in the second group (called suppliers).

Age Group	Respondents	(%)
56 or older	43	24
36 - 55	71	39
26 - 35	66	36
25 or younger	2	1
All ages	182	100 %

4.1. Expected benefits

The participants ranked how 3D printing would contribute to the companies' objectives of cost reductions, improving services, and storage space reductions on a five-point scale, from very low to very high. Those results are presented in **Figure 1**. The answers were slightly differentiated between the two groups of respondents. The majority of the supplier group considered the expectation of achieving all three goals to be very high, while the end-user group gave lead-in cost reductions. End-user participants considered cost reductions to be their most significant goal, while service improvement was mostly characterized by moderate importance and storage space reductions with a lower percentage. In contrast, supplier/stakeholder participants held the view that all given objectives were very important, with cost reduction, service improvement, and storage space reduction in sequence. However, both considered cost reduction as their vital objective among the three choices, with different values, namely: high importance, with 40 %, for end-user participants, while supplier/stakeholder participants holding them as very important, with a 52 % percentage. It is undoubtedly obvious that the main objective of companies is to reduce their expenses as much as possible. Cost reductions appear to vary as a goal for participating end users, even within their company role. The engine crew, as well as the technical department, rated cost reductions as of medium importance, with the technical department appearing to be more concerned about cost. This is completely understandable, because parts must be found when they are needed, despite the cost, but the budget must be kept within the specified limits. On the other hand, the participating owners/managing directors (senior managers), bridge crew, and procurement department were more cautious about cost reduction, as they preferred to save money.



Figure 1 Expectations regarding the company position for the two groups.

Source: Authors

4.2. Barriers

Regarding the obstacles (inhibitors) to the use of spare parts made with 3D printing, the participants of the end-user group considered that the most important aspect was the assurance of the quality of the spare parts made with new technology (54 %). Next was the know-how (26 %), regarding the difficulty in learning new technology, and skills of the staff (20 %). For the supplier/stakeholder group, the necessary know-how and quality assurance of spare parts came to the fore once again. The survey results on these barriers are shown in **Figure 2**.

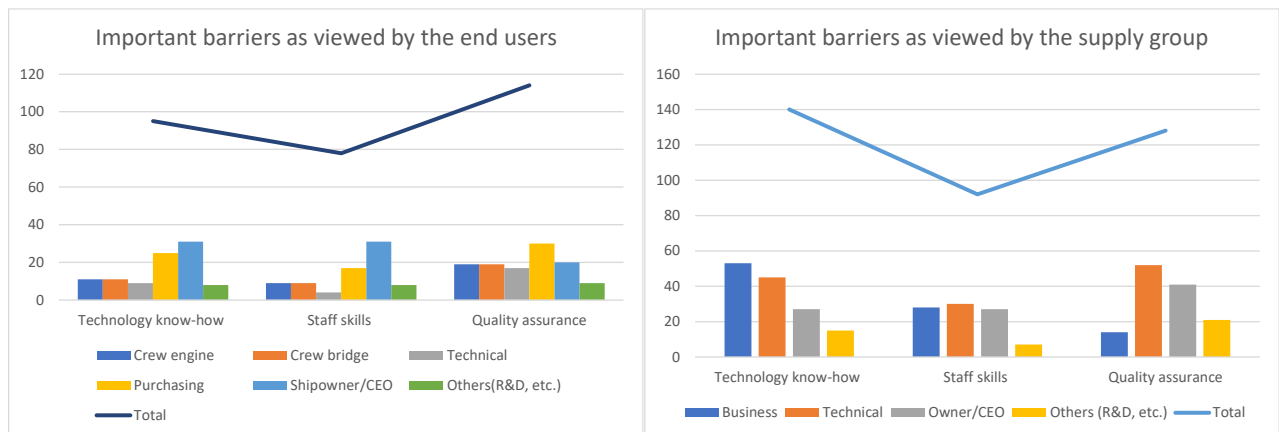


Figure 2 Important barriers according to the stakeholders.

Source: Authors

In addition, other important barriers, such as copyright protection and spare part digital files (required for printing), were clearly highlighted, followed by average importance for equipment availability, equipment costs (printer), staff skills, and required digital files (**Figure 3**). Judging both groups in terms of obstacles, quality assurance was undoubtedly the most vital obstacle, as all participants were concerned about how well the parts were made and the quality of the materials used in construction. The availability of material, know-how, and skills that must be ensured were deemed as essential for printing decisions. Having the decisions mentioned above, approvals, and resources, it was possible to follow an established project management methodology to implement AM in the supply chain successfully. Knowing the expected obstacles faced when 3D printing would be used to make spares can definitely help with better preparation in relation to all associated tasks.

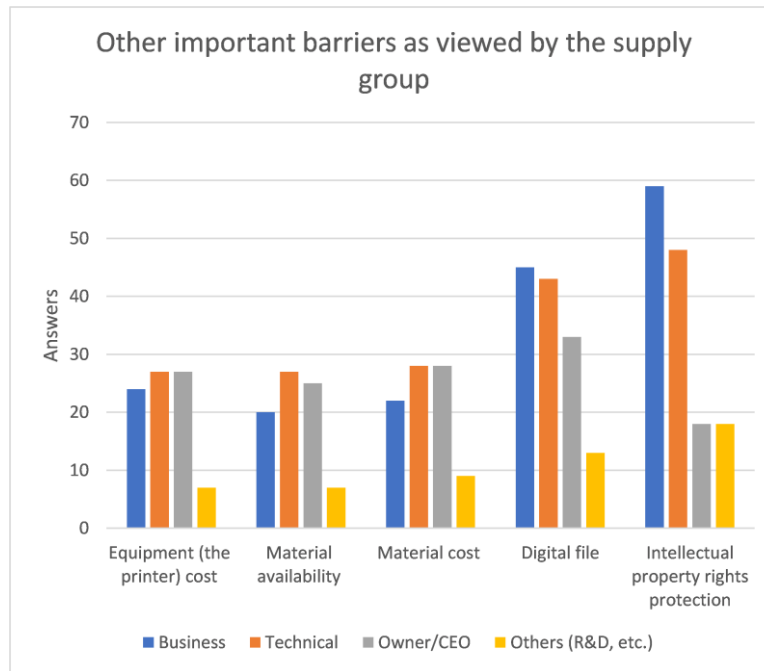


Figure 3 Other barriers as viewed by the supply group.
Source: Authors

4.3. Suitable spare parts for 3D printing

The options from the end-users for characteristics of suitable spare parts for printing appear as rare demand, high value, small size suitable for 3D printing and with a small lead of the rare demand feature. There were also other important features: small order quantity, short delivery time, and high supply risk were presented with relatively smaller percentages. The lowest percentage was noted for the choice of spare parts of high design complexity. Judging by the answers from the suppliers-stakeholders, the picture was similar to the previous group. A great percentage of the survey responders answered that, if 3D printing is applied, it would make repairs easier. One could note that all the answers from land office personnel were positive, since they know the cost a low-value spare can reach if transportation cost is included, leaving aside the difficulties in finding them (**Figure 4**). Academics were also positive.

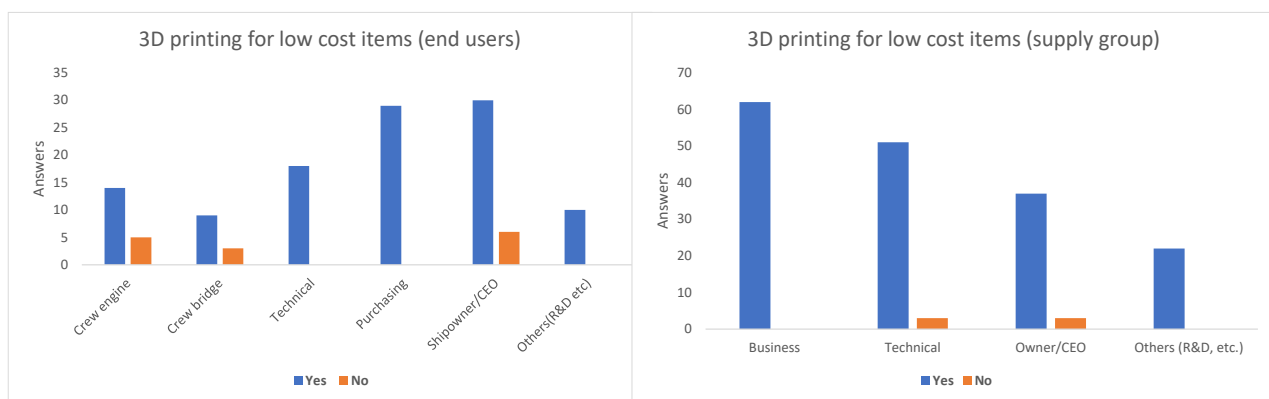


Figure 4 3D printing for low cost items.
Source: Authors

4.4. Available information when preparing/processing an order

The required information for the construction of spare parts along the supply chain, such as detailed construction plans, construction material, etc., as can be seen from the answers, does not

exist (Figure 5). The majority of respondents answered that they could only enter the code number of a spare part. However, some can improve location of the spare part when preparing the order using digital/electronic catalogues, hierarchical drop-down menus, or from simple image/sketch/drawing. Frontline technicians answered that they had a few more details available. However, not all the necessary info could be provided, even if they have the form of instructions for the planned maintenance at their disposal. The original equipment manufacturers provided only the necessary information to each group, in order to protect their copyrights. Since frontline technicians are involved in service, and have the knowledge to detect defaults, they were able to provide a few more construction details, but not all of the necessary ones. Perhaps the full required information could be obtained by “appropriate” reverse engineering methods. Perhaps then, the best solution could be to provide all the necessary information as an extension of the information system in use (following the copyright owner’s approval).

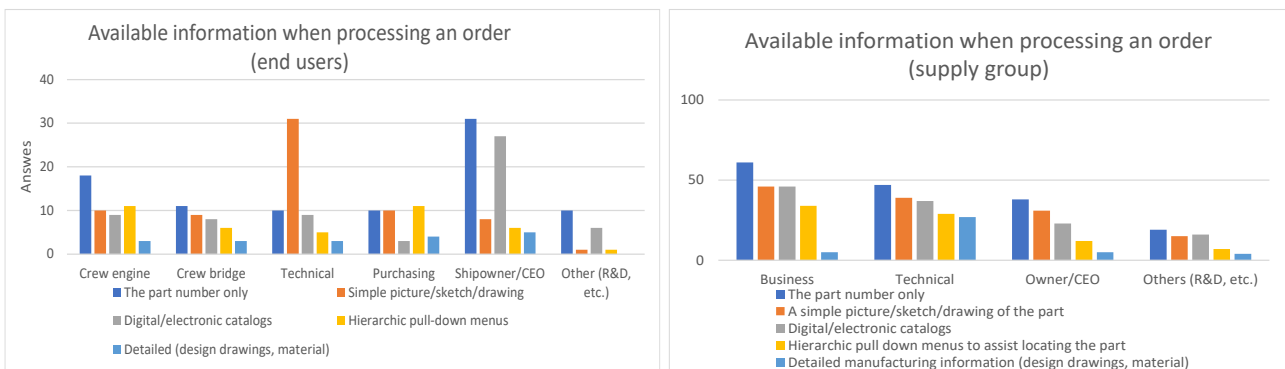


Figure 5 Available information when preparing/processing an order by the “end users” and “supply group”.

Source: Authors

5. Management perspective on the expected benefits

In this section, the objectives of the implementation of additive manufacturing from the CEOs’ and shipowners’ perspectives are depicted. Their opinion was regarded to be more than important, because of the fact that they are leading those companies, and (ultimately) take the final decisions for new investments in technology applications.

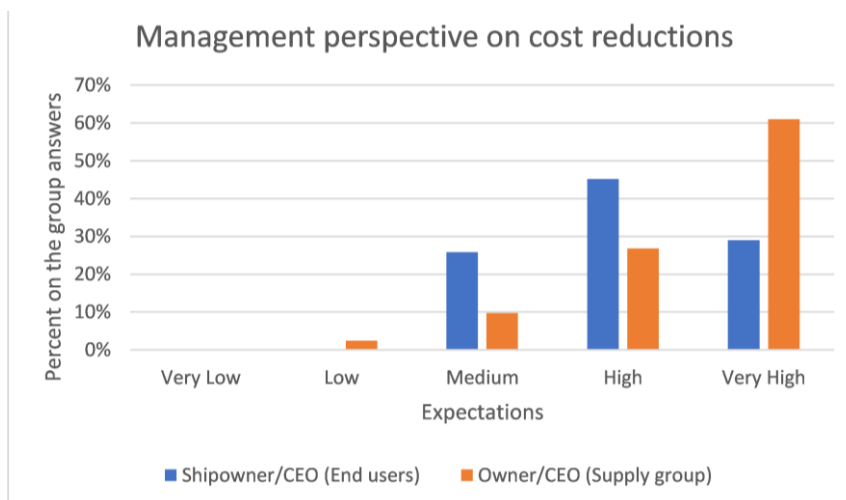


Figure 6 Management expectation on cost reduction.

Source: Authors

To begin with cost reductions, a differentiation regarding their expectations is shown in **Figure 6**. Owners/CEOs of the supply group ranked this perspective mainly as very high, with 61 %, then high, with 27 %, medium, with 10 %, and low, with 2 %. On the contrary, CEOs/Shipowners of the end users group ranked this perspective mainly as high, with 45 %, then very high, with 29 %, and medium, with 26 %.

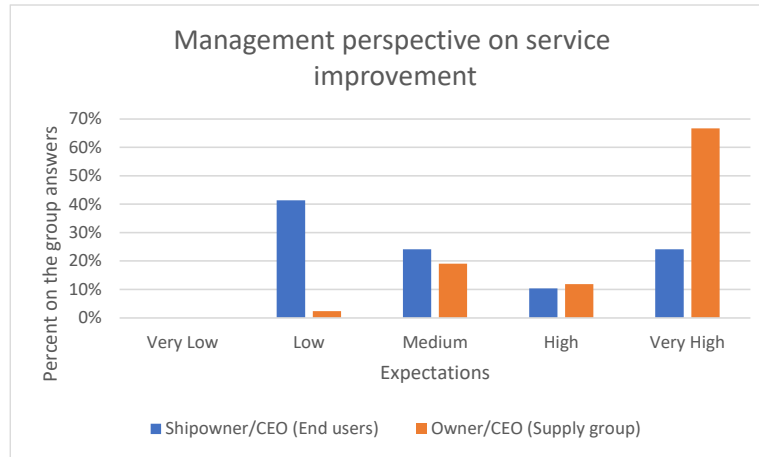


Figure 7 Management expectation on service improvement.
Source: Authors

As for service improvement, a huge differentiation regarding their expectations is depicted (**Figure 7**). Owners/CEOs of the supply group ranked this perspective mainly as very high, with 67 %, then medium, with 19 %, high, with 12 %, and low, with 2 %. In addition to CEOs/Shipowners of the end users group, they ranked this perspective mainly as low, with 41 %, then very high, with 24 %, medium, with 24 %, and high, with 10 %.

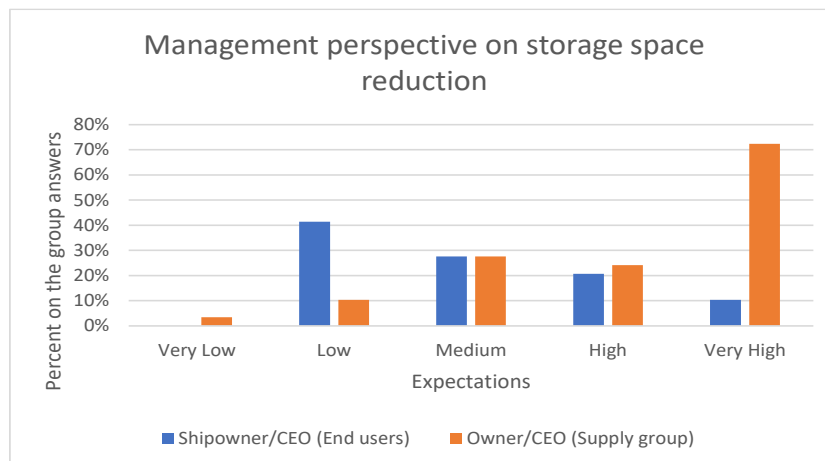


Figure 8 Management expectation on storage space reduction.
Source: Authors

Lastly, in terms of storage space reduction, once again, differentiation regarding their expectations was proved (**Figure 8**). Owners/CEOs of the supply group ranked this perspective mainly as very high, with 72 %, then medium, with 28 %, high, with 24 %, low, with 10 %, and very low, with 3 %. In addition, the CEOs/Shipowners of the end users group ranked this perspective mainly as low, with 41 %, then very high, with 10 %.

Looking at the above three objectives as a whole, cost reductions are shown to be of very high importance, both for Owners/CEO' of the supply group and for CEOs/Shipowners of the end users group. This is mainly because lessening the cost is one of the most important issues in the maritime industry. What is more, service improvement is found with differentiation in ranking by the two groups and, more specifically, with very high for Owners/CEOs of the supply group and with low for CEOs/Shipowners of the end users group. This could be totally understood regarding their roles and goals in the supply chain. Last but not least, storage space reduction is also ranked differently by Owners/CEOs of the supply group, ranked with very high, and by CEOs/Shipowners of the end users group, since Owners/CEOs find major difficulties in finding enough place for their stocks, as opposed to CEOs/Shipowners, whose main concern is the final spare part arriving at the place where it is needed.

6. Discussion

This research sheds light on the potential improvements in the structure of spare part supply chains in the maritime industry. It captures the perspectives of various stakeholders in the sector, from end-users to suppliers, and highlights factors that will facilitate or hinder the successful implementation of 3D printing technology.

The research reveals an interesting perspective on how participants ranked the expected benefits of 3D printing concerning their companies' objectives, specifically in terms of cost reductions, service improvement, and storage space reductions. It is evident that companies, regardless of their role in the supply chain, are driven by the need to minimize expenses. For end-user participants, the perspective is nuanced. While the engine crew and technical department see cost reductions as of medium importance, this is likely because they are more operationally focused, and understand that parts need to be available when needed. On the other hand, owners/managing directors, bridge crew, and the procurement department exhibit a more cautious approach toward cost reduction, possibly reflecting a preference for overall budgetary prudence. Having the part at the right place and time where and when it is needed offers the most benefits. Using passive stabilization platforms onboard moving research vessels, Phillips et al. (2020) successfully printed a number of parts with no noticeable differences from those produced in a traditional land-based laboratory. Silva et al. (2023) improved an on-board unstable condition 3D printing process by an automatic and electronic correction on the 3D printer machine itself. These are proof that parts can be made even onboard. Interestingly, service improvement is rated with moderate importance by end-user participants. This suggests that, while cost reduction is a primary focus for them, service quality is also a consideration. This perspective aligns with the idea that minimizing expenses should not compromise the reliability and quality of the services provided. Supplier/stakeholder participants see service improvement as very important, emphasizing the need for continuous enhancement of the services they offer.

In the case of storage space reductions, it is notable that both groups place less emphasis on this objective compared to cost reductions and service improvement. This may indicate that, while reducing storage space is a consideration, it is not the top priority. Companies understand the importance of having spare parts readily available and may be cautious about reducing storage space to a level that could hinder their operations.

The participants' perspectives on the barriers and obstacles associated with the use of spare parts made with 3D printing reveal important considerations for the successful adoption of this technology. Barriers such as quality assurance, the need for knowledge and skills, copyright protection and the management of digital files, and the availability of equipment, are vital to address, as they can significantly impact the implementation and overall effectiveness of 3D printing in the maritime industry. Ensuring compliance with international maritime regulations and safety standards is paramount. Organisations, such as ISO, ASTM, NASA, SAE AMS, ASME, AWS, API, VDI, IEEE, DNV, BV, LR, ABS, UL, and TÜV SÜD, have devoted themselves to the qualification and

certification of metal AM (Chen et al., 2022). Among them, the classification societies will ensure compliance with international maritime regulations and safety standards in the maritime industry. In Additive Manufacturing, the protection of intellectual property rights for the digital files of spare parts is a concern. The safeguarding of these rights is crucial, particularly when digital files are shared or distributed across the supply chain. This aspect may involve legal and contractual considerations. The use of technological protection measures in digital supply chains may help address IP security issues, but should be balanced with IP exceptions to avoid overprotection and negative impacts on innovation and sustainability (Adu-Amankwa & Daly, 2023). Upskilling and reskilling programs can help employees gain new skills to adapt to this emerging technology (Illanes et al., 2018).

The preferences and opinions of both end-users and supplier/stakeholders regarding the characteristics of suitable spare parts for 3D printing provide valuable insights into the practical application of this technology in the maritime industry. These characteristics are crucial for identifying which spare parts are best suited for 3D printing. End-users and supplier/stakeholders overwhelmingly agree that spare parts with rare demand and high value are the most suitable candidates for 3D printing. Spare parts with characteristics that allow for small order quantities and short delivery times are also considered suitable for 3D printing. Parts with a high supply risk, which are difficult to obtain through traditional supply chains, are seen as prime candidates for 3D printing due to the potential to provide reliable access to otherwise hard-to-find or delayed parts. Both groups showed less preference for spare parts with high design complexity. This suggests that simpler designs are more practical for 3D printing and can be produced more efficiently. It is noteworthy that academics and land office personnel provided positive responses to the idea of using 3D printing for spare parts. This suggests that individuals with knowledge of the maritime industry and its logistical challenges see the potential benefits of this technology, particularly in terms of cost savings and accessibility. The response to the printing of low-cost spare parts differed from the literature (Final Report Pilot Project 3D Printing of Marine Spares, 2016; Kandukuri, 2019), for which the response of the participants was positive. However, information available for the manufacture of spare parts seems to be scarce.

The availability of essential information for the construction of spare parts along the supply chain is a critical factor in the successful implementation of 3D printing technology. The participants' responses shed light on the current state of information accessibility and its implications. The majority of participants, both end-users and suppliers, reported that they can only access the code number of the spare part. This limited information restricts their ability to manufacture spare parts through 3D printing effectively. It is clear that comprehensive construction plans and material details are often unavailable. Some participants mentioned using digital/electronic catalogues, hierarchical drop-down menus, or simple images/sketches/drawings to locate spare parts when preparing orders. While these sources provide some information, they do not typically contain the detailed construction plans and material specifications required for 3D printing. Frontline technicians, who are directly involved in servicing equipment, tend to have more knowledge about spare parts and may be able to provide some additional construction details. However, even with their expertise, they often cannot provide all the necessary information for 3D printing. Original equipment manufacturers (OEMs) are cautious about sharing detailed construction information to protect their copyrights. This is a common practice in many industries. While they provide the necessary information for servicing and repairs, they may withhold certain proprietary data to maintain control over their designs. Reverse engineering can be a complex and time-consuming process, and its feasibility may vary depending on the spare part in question. The best long-term solution may involve providing all the necessary information as an extension of the existing information system, subject to approval from copyright owners (such as OEMs). This approach could streamline the process of accessing the required data for 3D printing while respecting copyright protections.

The perspectives of CEOs and shipowners from both supply and end-user groups regarding the expected benefits of implementing Additive Manufacturing (AM) in the maritime industry

highlight their distinct priorities and goals. This differentiation in expectations is particularly noteworthy, as these individuals play a pivotal role in making decisions on technology investments. Owners/CEOs in the supply group prioritize cost reductions, while CEOs/Shipowners in the end users group focus on service improvement. For Owners/CEOs, service improvement and storage space reduction are also significant priorities. In contrast, CEOs/Shipowners in the end users group rank service improvement as a lower priority, with a primary concern for ensuring spare part availability. This perspective reflects their challenges in managing inventory and storage space. CEOs/Shipowners in the end users group rank storage space reduction with less emphasis. Their primary concern appears to be ensuring the availability of spare parts when needed, rather than space constraints.

7. Conclusions

Today, various advanced digital technology applications are utilised at an unprecedented pace, causing disruption across all levels of business.

The digitization process of the spare part supply chain with the introduction of AM involves factors that will push it forward, and others that are likely to be an obstacle to it. The traditional linear manufacturing model in the marine supply chain needs to transition to a circular approach, embracing innovative upcycling solutions and adopting AM suitable for repairing and remanufacturing industry components (Pavlopoulou & Kostidi, 2021). 3D printing could be an enabling technology for the Circular Economy (Silva et al., 2023). This work extends previous work (Kostidi et al., 2021) that presented the end-user views (onboard the vessel and at the land office), upstream (original equipment manufacturers, subcontractors, regional or local distributors, suppliers, traders) in the maritime industry. By capturing the stakeholders' views and expectations along the whole SPSC (starting from the maker of the part and including, of course, the end-user), this paper aims to assess the industry's readiness to accept this new digital technology application and identify the most influential factors for its successful implementation.

The participants' ranking of expected benefits in the context of 3D printing provides valuable insights into the priorities of companies in the maritime industry. The maritime industry's pursuit of cost reductions through 3D printing is evident. However, it is essential to recognize the industry's commitment to maintaining service quality and operational readiness. Companies are carefully assessing how 3D printing can serve their objectives while ensuring that cost-saving measures do not compromise their ability to deliver reliable and efficient services.

Understanding and addressing the barriers (the paramount importance of quality assurance, the essential need for skills and knowledge, the pivotal aspect of digital asset management and copyright protection, and the challenges related to equipment availability and costs) is vital for the effective implementation of 3D printing in the maritime industry. By proactively managing these challenges, companies can better prepare for the adoption of 3D printing technology and enhance their spare part supply chain processes. Overcoming these obstacles is essential to fully realize the benefits of 3D printing while ensuring the reliability and safety of maritime operations.

The characteristics that make spare parts suitable for 3D printing is decisive for effective implementation in the maritime industry. Leveraging this knowledge, companies can identify and prioritize parts that can benefit the most from 3D printing, thereby enhancing supply chain efficiency and cost-effectiveness.

Addressing the challenge of information accessibility is essential for the successful integration of 3D printing technology in the maritime industry's spare part supply chain. Balancing copyright protection with the need for comprehensive data is essential to ensure the reliability and efficiency of maritime operations.

To facilitate the broader application of the research findings in various maritime and port environments across Europe and globally, it is crucial to employ a range of strategies, including comparative studies, industry surveys, case analyses, regulatory evaluations, environmental impact assessments, and continuous monitoring of technological advancements. By leveraging these

strategies and taking into account the multifaceted considerations at play, this research has the potential to serve as a foundation for a comprehensive understanding of the implementation and adaptation of AM technology within diverse maritime (port) settings worldwide. This expanded perspective can contribute to the development of best practices and strategic approaches for optimizing spare part supply chains in the broader maritime industry on a global scale.

The authors have attempted to provide the stakeholders' views at the end of the chain on board the vessels and the land office and upstream (makers, suppliers), pointing out factors that will benefit and those that are likely to be obstacles. The present study is one of the first approaches to the study of the SPSC in maritime and could be continued with further investigation. Furthermore, the field of AM is constantly evolving. Thus, it is necessary to periodically re-evaluate the technological achievements and their effects.

8. Future research

While this study provides valuable insights into the perspectives of stakeholders in the spare parts supply chain (SPSC) regarding the implementation of Additive Manufacturing (AM) technology in the maritime industry, several areas warrant further investigation:

Given the dynamic nature of technology, it is crucial to delve into the long-term viability of AM within the maritime SPSC. Future research should assess potential advancements, market trends, and potential disruptors that may impact the technology's effectiveness over time. Understanding how AM can remain relevant and competitive in the evolving maritime industry is essential.

While this article acknowledges cost reduction as a primary goal, a more comprehensive cost-benefit analysis is necessary to quantify the potential savings and investments associated with AM adoption. Future research should delve into not only the cost of equipment but also factors like material costs, maintenance, and training expenses. A thorough analysis will provide a clearer picture of the economic implications of AM.

The study mentions the benefits of AM in terms of reducing inventory and minimizing delays, but future research should address the environmental impact of increased additive manufacturing. This should encompass considerations related to material waste, energy consumption, and overall sustainability. Conducting a Life Cycle Assessment (LCA) will be crucial to comprehensively assess the environmental footprint of AM in the maritime industry.

As highlighted in the article, the dynamic nature of the industry, especially in the post-COVID era, necessitates ongoing evaluation. Future research should focus on re-evaluating the effectiveness of AM, taking into account changes in the supply of spare parts and sustainability considerations throughout the entire product lifecycle. Continual assessment is essential to adapt to evolving industry demands.

These avenues of further research will contribute to a deeper understanding of the long-term prospects, economic implications, environmental consequences, and evolving dynamics of AM technology in the maritime SPSC. They will help shape strategies and decisions in this rapidly changing industry.

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