Additive Manufacturing of Spare Parts in the Maritime Industry: Knowledge Gaps for Developing a Norwegian AM-Based Business Ecosystem for Maritime Spare Parts

Gunnar Lamvik
SINTEF Digital, Trondheim, Norway
gunnar.lamvik@sintef.no
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Abstract: Additive Manufacturing (AM), also known as industrial 3D printing, is a high skill technology that can improve the safety level in the maritime industry, reduce costs for the actors and lead to environmental improvement in the shipping sector. Reaping the benefits of AM in the spare part supply chain requires adjustments in the entire business ecosystem. This paper reports findings from semi-structured interviews and conversations with industry stakeholders to assess the knowledge needs. It identifies ten companies that are engaged with AM in either the offshore or maritime sector and provides insights into the main challenges that needs to be overcome. We find that additive manufacturing of spare parts in shipping is looking more and more realistic, and that the first commercial deliveries of non-critical parts have already taken place. But as the adoptation of the technology is still in the initial stages, a lack of knowledge and understanding is a major obstacle, both among suppliers, end users and in the national government. The key contribution of the paper is to recommend ways to expand on existing knowledge to maintain the current momentum.

Keywords: Additive manufacturing, digitalization, maritime industry

1. Introduction

Additive manufacturing (AM) is a term covering several production methods where material is autonomously fused together in layers to form a part based on a digital representation of the part. A well-known version of the concept is Fused Deposition Modeling (FDM) – a 3D-printing process with polymer filaments, but the range of materials that can be used in AM also includes metal alloys, ceramics, concrete and more. The additive approach to manufacturing has distinctive benefits compared to subtractive production methods and molding techniques, but it also requires new skills and knowledge at both the individual, organizational and inter-organizational level. To fully benefit from AM, whole supply chains and business ecosystems must be redesigned.

In this paper, we study the efforts to build a business ecosystem for AM in Norway, based on the needs of the maritime industry to have spare parts produced locally and on-demand. We present some of the key companies that are positioning themselves to play a role in the future value chain and document their ideas about the competence and knowledge needed to build a new AM-based ecosystem for after-sale parts in the maritime sector. The data is collected from semi-structured interviews, workshop participation and conversations with industry stakeholders.

We propose that the maritime industry is well suited for introducing and testing new production technologies. Large shipping companies can be described as having a highly distributed organization, which favors local production in multiple sites. With vessels spread across the globe and a crew often from different nations, large shipping companies represents a type of organization that 1) is well suited for localized production solutions and 2) have the financial capacity to lead fundamental transitions in value chains.

Developing an ecosystem for additive manufacturing in shipping can also bring benefits to other industries. E.g., in Norway there have been several attempts in the energy sector to attract suppliers that can support the digitalization of maintenance, repairs and refurbishment activities. The results reported in this paper will help decision makers in government and private companies better understand the benefits and challenges related to additively manufactured spare parts.

The paper starts with defining the scope of the study and explaining why we focus on the maritime industry in section 2. Section 3 describes the qualitative research method that was used, and the results are presented in section 4. We discuss the findings in section 5 before making concluding remarks about policy advice and suggested direction for future research in section 6.

2. The current status for AM production of spare parts

2.1 The potential benefits of large scale additive manufacturing

AM is often used in the design process of new parts through prototyping, but it is traditionally regarded as too expensive for final production. In recent years, AM has been suggested as a promising technology for the production of spare parts and is already being used for this purpose in the aviation and automotive industries to a limited extent (Knofius, van der Heijden, and Zijm 2019; Kunovjanek, Knofius, and Reiner 2020). One important benefit is that AM is especially suited for producing individual products and short production series, where the economy of scale of traditional manufacturing does not apply. A special case are obsolete parts that are not readily available. Another benefit is that AM can allow decentralized production near end users, thereby reducing transportation needs. Thirdly, the possibility of on-demand production reduces the need for warehousing of physical, often slow moving, parts. In industries where short lead times are critical, original equipment manufacturers (OEM) typically end up holding large volumes of parts that binds up capital.

Redesigning supply chains to utilize AM comes with trade-offs. For example, Thomas (2016) sees adopters of AM as trading controllability for flexibility. Holmström et al. (2010) and Khajavi, Partanen, and Holmström (2014) explore the implications of moving from centralized to decentralized production of spare parts for airplane manufacturers. The see one benefit of centralized production as easier control of the production process. Secondly, the authors point out that airplane customers have access to purchase maintenance kits containing the most common spare parts, which essentially moves some of the burden of holding parts from the OEM to the customer and reduces the lead time when those parts are required. Thirdly, the costs of buying and operating multiple AM-machines at different locations may be prohibitively high.

In recent years, advocates of additive manufacturing have paid more attention to the environmental impact of AM. Most studies focus narrowly on a single product or production process. An exception is Möller et al. (2019) who compare the carbon footprint of various alternative AM technologies and conventional CNC-milling by life-cycle assessment (LCA). They find that the efficient material usage of AM processes more than makes up for the extra energy and time required to make the part. Faludi and Van Sice (2020) reviews the existing literature and found that the environmental impact of AM depends crucially on the part geometry, feedstock material and the need for tooling. This implies that manufacturers need to take many factors into account when deciding which manufacturing process to invest in.

The current study compliments the existing literature by regarding the spare part supply chain not as a two-sided market of sellers and buyers, but as a business ecosystem with multiple stakeholders fulfilling different roles. As such, the industrialisation of AM depends on the coordinated development of multiple business models and the regulatory framework, in addition to the acquisition of new technical skills at multiple organisations throughout the supply chain.

2.2 Change agents in the maritime industry

International shipping is one of the one most pollutive sectors in the world when it comes to carbon dioxide (CO_2), an important greenhouse gas. This has come to been seen as a major problem and something that has to be solved in the near future. In 2018, the International Maritime Organization (IMO) adopted an initial strategy on the reduction of greenhouse gas (GHG) emissions from ships, setting out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible. The initial strategy of the organization was to set a target to reduce CO_2 emissions from international shipping by at least at least 40% by 2030, pursuing efforts towards 70% by 2050.

In 2020, the European Parliament introduced the "EU Regulation on the Establishment of a Framework to Facilitate Sustainable Investment", or the so-called "Taxonomy Regulation". The new EU-taxonomy on sustainable finance aims to provide businesses and investors with a common language to identify to what degree economic activities can be considered environmentally sustainable. The IMO-strategy and the EU-taxonomy is making a real impact. Norway is a major shipping nation, and from 2030 the Norwegian Shipowners' Association members will only order vessels with zero emission technology. From 2050, the Norwegian fleet will be climate neutral. In this effort, any new technology is of interest if it can make the fleet more climate friendly.

By making large investments in technologies such as scrubbers for cleaning exhaust gasses, the maritime industry has proved itself to be innovative and able to take on large challenges. This makes it a potential candidate for spearheading the move to additive production of spare parts. Particularly if AM can be shown to provide good quality parts with reduced climate footprints. The potential is there for companies within the industry to act as change agents, i.e. actors that are influencing others to change. Notably, while Wahab et al. (2018) discuss the need to remanufacture large structures, such as hulls and vessels, they also note that many components, such as engines, compressors and pumps are already being remanufactured already. This shows that the concept of a circular economy and sustainable shipping is not entirely new in this sector. Milios et al. (2019) found that high costs, lack of policy framework and lack of organisational competency are the main obstacles for increased reuse and remanufacturing of ship components in the Scandinavian maritime sector.

3. Methodology

The aim of the current study has been to engage with key stakeholders to identify the knowledge gaps that need to be filled in order to develop a value chain for spare parts in the maritime industry. The work took place in the span of four months, from January to April 2021. A two-step process was applied that involved efforts to identify relevant stakeholders in the first step and data collection through semi-structured interviews and conversation in the second step.

For the first step, we used social networks, online sources, literature search and AM-related seminars to identify companies that we wished to contact. Our research organization is host to a research center on manufacturing, called SFI Manufacturing, where most of the AM related research at our research organization is organized. We obtained recommendations about which companies to contact from our colleagues who have an extensive network in the Norwegian manufacturing and AM communities from decades of applied research on metal AM.

The most prominent attempt at developing a Norwegian AM ecosystem has come from the energy sector. We attended the first virtual seminar of the Norwegian Energy AM network organized by Energy Valley, an interest organisation for energy related companies, and recruited sources by presenting our study idea to about 70 participants. We also participated in a virtual seminar arranged by the Danish AM hub on the environmental sustainability of AM, two virtual seminars arranged by the Nordic 3D-printing service company PLM Group and two virtual seminars by the US based 3D-printing company Markforge. In the end, attending the international seminars did not result in additional participants to our study, but they led to improved understanding of the subject matter.

When we identified a company of interest, we searched their webpages and online news outlets for information about their AM-related activities. From this, we made a list of 11 companies that we reached out to for interviews. One 3D-printing company did not respond to our request, while the others approved to be interviewed.

For the second step we designed an interview guide covering the following topics:

- Personal and company background
- Ongoing and planned AM activities in the maritime and off-shore sectors
- Perceived knowledge needs and the availability of skilled personnel in Norway
- The sustainability aspects of AM

The guide was used as a template for semi-structured interviews and conversations. The guide functioned as a reminder to the researchers about what were the main topics we wanted address, but we also allowed the conversation to go in the direction of the interests of the participants. This open approach aided the flow of communication and let to a relaxed mood that allowed the participants to express themselves freely. The interviews were set up using Microsoft Teams with a tentative duration of 45 minutes. The interviews were transcribed and coded using a grounded theory approach where the empirical data guided the topics used for open in-vivo coding (Vollstedt and Rezat 2019). The codes were used to denote *concepts* and *categories* that were used in a structured analysis of the interviews.

Some of the interviews led to agreements to apply for research projects and this spurred subsequent conversations of varying length and duration. These conversations were not transcribed as they aimed to define research topics that we agreed to explore in later studies. Instead, extensive notes were taken that provides additional information to our study. In two cases, the initial subject recommended another person within the organization that we should talk to and this was arranged. In total, we interviewed and engaged in conversation with 18 persons from ten companies. The companies are registered in four different countries, but all except Dansk AM Hub have activities related to AM in Norway. Table 1 lists the companies that we engaged with and lists the number of interviews and conversations that were had. It also indicates the number of participants and their roles within the organizations.

Table 1: Summary of interview and conversation participants

Company	Interviews	Conversations	Number of participants	Country
Additech AS (Prototech)	1		2: CEO + engineer	Norway
Dansk AM Hub	1		1: Engineer	Denmark
DNV AS		1	3: Group leader + 2 engieneers	Norway
Equinor AS	2		3: Director for digitalization + maintenance engineer + business developer	Norway
F3nice SrL	1	2	2: CEO + engineer	Italy
Fieldmade AS		2	2: CEO + CTO	Norway
Ivaldi Group AS	1	3	2: CEO + business developer	USA
Kongsberg Maritime AS		1	1: Chief engineer	Norway
Nordic Additive Manufacturing AS		1	1: CEO	Norway
Wilhelmsen Ships Service AS	1	3	1: Head of venture	Norway
Total: 10	7	13	18	4

Note: CEO = Chief Executive Officer, CTO = Chief Technology Officer. Engineer refers to an employee with technological education at the level of Master of Science or above.

4. Results

The interviews revealed a large interest in the topic from the side of the subjects themselves. Not surprisingly, the focus shifted between the sessions and many topics came up. We present the results according to what we see as the most important core categories (categories of categories) for understanding the barriers and opportunities for AM spare parts in the maritime industry. The quotes are translated from Norwegian.

4.1 Education, skills and learning

Additech, a newly formed subsidiary of Prototech, has worked on an AM use case with Equinor, Norway's largest oil and gas company. They see a lack of skills as a large barrier to widespread AM adoptation. The need is both to see when AM is suitable, and when it's not.

"*Without understanding AM, the industry will not use it*." - Additech CEO.

"*AM is not suitable for 98% of the suggested components*." - Additech CEO.

Additech is running a pilot class where they train 12 persons in AM over two years. They think it will take a very long time before AM-competency is widespread in the industry. They have also proposed to the Vestland county council to develop an AM course as part of vocational education at a local high school. Currently, AM is only taught in Norway in higher education. In Denmark it's even less:

"In Denmark there is no education given in AM. Not even at the Bachelor and Master level." – Dansk AM Hub Engineer.

4.2 Certification

There already exists procedures for certifying manufacturers for AM of spare parts to the maritime sector. Classification company DNV, developed such guidelines in 2017 and released their first approval of manufacturer scheme in 2018, but there has been little interest from the industry to use it.

"The spare part idea is a slow-burning business case." - DNV Engineer.

From conversations with Fieldmade, it's apparent that the existing guidelines are not well suited for AM production in a distributed supply chain. The certification process assumes that the manufacturing process takes place at a given centralized location, while they want to be able to utilize a network of suppliers with the certified

AM equipment. Also, the need to ship product samples to a centralized location for testing removes some of the rationale behind decentralized production.

Equinor is also not satisfied with the current status of certification of 3D-printed components:

> *"Certification of items is a path that needs to be mapped out."* Equinor Director.

DNV sees a need to certify virtual inventories, as opposed to individual parts. They point to the need to verify that the new distribution models actually deliver on reductions in lead times, etc.

Additech pointed out that certified equipment is locked to a given set of material and production parameters, which mean that the machine cannot be used for experimentation. Additech also mentioned that a certificate is difficult to obtain for smaller companies because they need to handle a lot of information. They argue that it may create an entry barrier that hinders both collaboration and competition.

> *"A customer may qualify us as a supplier, but it's hard for smaller companies to collaborate and achieve the same."* – Additech Engineer.

4.3 Benefits of AM produced parts

The main benefits of AM that were mentioned were price and lead times. E.g. Additech has printed heat exchangers that led to 30% reduction in price and 80% reduction in manufacturing time.

Equinor sees many benefits of AM, especially with regards to digital inventories of spare parts. This can cut costs and give substantial environmental benefits. However, the extent of the environmental impact is not known since they do not know the carbon emissions of their suppliers. Upstream emissions in a value chain are referred to as "scope 3" in climate gas accounting. One example that was mentioned is that you only print as many parts as you need while purchases of finished products are commonly done in bulk. With gaskets, expiration dates mean that many are simply thrown away without being used.

> *"Equinor has 27 bln. NOK in storage (about 3,3 bln. USD) of which 80% is never used."* – Equinor Director.
>
> *"The large emissions are in scope 3, where we don't have the numbers. We don't know the emissions. […] Here we are blind."* – Equinor Director.

Kongsberg Maritime sees a business opportunity in home sourcing production. They are in a process where they collect scope 3 emissions from suppliers and have been surprised to learn how high the emissions actually are on parts made in the far east.

> *"We should promote how green our production is."* – Kongsberg Maritime Chief engineer.

Dansk AM Hub has commissioned a report on the AM ecosystems in Scandinavia that includes thoughts on the environmental aspects (Olsen et al. 2020). The subject sees the sustainability aspects of AM as a new and rising topic. When asked about shipping giant A.P. Møller – Mærsk, the engineer answered: "They have started to look at AM, but it's uncertain to what extent. Perhaps it is secret?"

4.4 Singapore JIP

AM as an on-demand production, has been tested and practiced in a so-called JIP (Joint Industry Project) in Singapore, initiated by the Maritime and Port Authority of Singapore. The consortium is led by Norwegian company Wilhelmsen Ship Service (WSS) and includes original equipment manufacturers (OEM) Wärtsilä, Kawasaki Heavy Industries and Hamworthy pumps, independent assurance and risk management expert DNV, technology partners ThyssenKrupp, Ivaldi Group and Tytus3D, and several end users: OSM Maritime Group, Thome Ship Management, Carnival Maritime, and Berge Bulk. In total 13 actors work together in this collaboration which aim is to test and be more familiar with AM production in the maritime cluster.

This JIP represents a potential breakthrough in the field of AM production in the maritime industry as they print real spare parts for actual companies. In February 2020, the first commercial delivery of 3D printed parts in the maritime industry took place. It included 3D printed scupper plugs and ventilation grids for Berge Bulk. In all, the JIP identified about 100 non-critical parts that are suitable for AM.

Conversations with Wilhelmsen Ships Service and Ivaldi Group revealed that key personnel involved in the JIP are relocating to Norway in 2021. These are the representatives from Wilhelmsen Ships Service and DNV. In addition, Ivaldi Group is moving their headquarter from California, USA to Norway, and Italian company F3nice SrL has registered a subsidiary in Norway in May of 2021, F3nice AS. F3nice has proprietary technology for recycling high value scrap metals to metal powders used in AM. As such, some of the leading competency on AM spare part production for the maritime industry in the world will soon be located in Norway. All these companies have expressed a strong interest in further developing the business ecosystem for spare parts in the maritime industry.

Wilhelmsen Ships Service claims to serve more than half of the world's fleet of ships above 300 dwt (deadweight tonnes) and are active in 2200 locations around the globe. They explained that the average age of the fleet is about 21 years and that each ship purchases spare parts for about 50 000 USD annually. By providing obsolete parts, and parts with improved performance and/or lower price, modernisation of the fleet can happen sooner than if the ships were to be equipped with traditionally manufactured parts. E.g., it is possible to build parts with integrated sensors that registers heat and vibrations, and this digitalisation can be used in predictive maintenance programmes.

Ivaldi Group highlighted the environmental costs of transporting parts internationally by ship or plane, as is often the case with centralized production. They also see a large potential for digital inventories and are looking into software solutions that can integrate digital inventories with existing inventory management systems. They see IPR-management as an important aspect that needs to be addressed if OEMs should make their designs available for downloading through a third-party platform.

5. Discussion

The results illustrate the large potential that an AM based supply chain for spare parts can have in terms of business opportunities and environmental impact. The emerging research trend of evaluating carbon reductions through additive manufacturing fits well with the stricter reporting requirements that maritime companies are facing. The convergence of key persons to Norway in 2021 creates good conditions for setting up new collaborations and next steps in reforming the value chain.

The lack of skills and understanding of the AM processes were presented as a major obstacle. These comments came predominantly from actors with experience from the offshore energy sector where the push for reforming the supply chain has come from an end user, Equinor. Here suppliers seem content with their current business model, and any savings for the end user implies a loss for them. For the maritime industry, the situation is different. In the model provided by the Singapore JIP, it is a third-party service company, Wilhelmsen Ships Service, that is responsible for providing the parts that customers need. As such, the end users do not require extensive knowledge about the production technology. For generic parts, the service company is free to choose any provider they wish that can provide the part, certified when required. In this model, the incentives for supplying AM produced spare parts are aligned with the interest to buy it, and certification requirements and documentation of environmental impact may be more important. Wilhelmsen Ships Service can be seen as taking the role as a change agent in the industry.

It is an open and empirical question to what extent tacit knowledge and preconceived perceptions will work to hinder the adoptation of AM in the maritime industry. Our impression is that adoptation is hindered more from a lack of knowledge, than by conservatism. At this early stage, any delivery of 3D-printed parts will function as a boundary object that will help people to learn more about the opportunities and limits of AM produced parts.

Today, there is no common arena for actors in the spare part ecosystem to come together to coordinate their efforts. One way to create this is to establish an AM network such as the newly established Norwegian AM Energy network. Another alternative is the formation of a Joint Industry Project similar to the one led by Wilhelmsen Ship Services in Singapore. The Singapore JIP was a result of a national strategy to promote the industrialisation of AM in Singapore. In Norway, AM does not currently have the same strategic backing from the government. Highlighting the environmental aspects of AM, in addition to the potential for significant value creation, may help to reframe AM as worthy of government support after several past "hype cycles" in 3D-printing.

Due to limited time and resources, the selection of interview subjects focused on companies with a relation to the maritime industry. For this reason, we did not include other Norwegian manufacturing companies with strong AM competence, such as Tronrud Engineering AS, Norsk Titanium AS, Sandvik Teeness AS and others. We also excluded software developers and material scientists, even though they also represent important stakeholders in an AM-based business ecosystem. The narrow focus likely led this study to overlook several aspects of ecosystem development. The choice was deliberate and although some readers can understandably regard this as a weakness, we prefer to think of it as opportunities for future research.

6. Conclusion

The study identified ten companies with an interest in the development of an AM based value chain for spare parts to the maritime industry. They represent core functions of a future business ecosystem, including the production of feedstock, parts design, manufacturing, maintenance services, and certification. Like the maritime industry itself, most of these companies have an international reach and already serve customers across the globe. This suggests that large scale industrialisation of AM in Norway may come through the maritime industry. Once established, the ecosystem may expand to cover other sectors as well, e.g. the energy and transportation sectors.

Through interviews and conversations with industry stakeholders, the study shows that knowledge management will be crucial to realize the promise that AM holds for a greener and safer maritime industry. The study suggests focussing on 1) methods for identifying spare parts suitable for AM, including training of procurement staff, 2) documenting the environmental benefits of an AM-based spare part supply chain through lifecycle assessments and environmental risk assessment, 3) building trust in AM through improved certification schemes for parts and manufacturers, 4) linking education in AM to vocational studies, 5) IPR-management and 6) establish a platform for coordinated development of cooperation and business models.

AM can disrupt the maritime spare parts supply chain to support a safer and greener maritime industry. With the new EU taxonomy for sustainable finance, AM proponents have one more argument in their favour and the first market-based transactions have already taken place. The technological platforms are developing rapidly and more research will be needed to fully understand the economic, social and environmental impacts of this shift.

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