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Additive Manufacturing in the Maritime Industry: Impact on Production Processes, Workers, and End-Users

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ABSTRACT

Additive Manufacturing (AM) technologies are revolutionising global production processes, offering substantial benefits to the maritime industry by eliminating the reliance on models and moulds. This shift toward a sustainable, zero-waste future presents significant opportunities and considerations for both workers and end-users. The adoption of automated 3D printing necessitates workforce retraining, with a focus on digital technology skills, reducing the reliance on manual labour. Proactive training programs are vital to equip operators for this evolving landscape. Additionally, studies are exploring occupational health-related aspects of 3D printing, assessing whether it could create a safer working environment compared to traditional manufacturing processes. AM customisation capabilities empower designers and engineers to prioritize human factors, enhancing user experience, comfort, and usability. This approach fosters innovations aligned with the preferences and needs of end-users. This paper aims to explore the impact of AM technologies on manufacturing processes and design freedom within the maritime industry, emphasizing opportunities for improved efficiency, sustainability, and adaptive design practices to meet the sector's dynamic needs.

Keywords: Maritime industry, Additive manufacturing, 3D printing, Redefine the roles of workers

INTRODUCTION

Thanks to the gradual cost decrease over the past few years, additive manufacturing (AM), also known as 3D printing, has gained more popularity and became more and more adopted among several industries, including automotive, biomedical, aerospace, and maritime, although to a lesser extent than the others mentioned (Boissonneault, 2019). AM can be employed for a full range of applications, such as rapid prototyping, studying product ergonomics, and end-to-end product manufacturing, meaning that it can significantly influence the entire production process, spanning from the creation of a preliminary model to the finalisation of fully assembled products (Jarža et al., 2023).

These additive technologies are based on a process where a digital model is sliced into layers, and these layers are then built up one on top of the other to create a physical object (Gibson et al., 2015, Khajavi et al., 2014). The layer-by-layer approach demonstrates its capability to produce complex shaped components without requiring traditional machines (Ponche et al., 2017). This zero-tools methodology therefore enables greater flexibility in production, enhancing mass customisation, where products are designed to meet the customer's needs or desires, as well as mass personalisation, where unique artifacts are manufactured for each individual (Ford and Dean, 2013). Design freedom offered by 3D printing facilitates the transition to a more sustainable production process, as optimised lightweight structures can be manufactured by strategically positioning material only where needed, thus effectively minimising waste generation (Hao et al., 2010).

Maritime industry stands to gain substantial advantages from the progress brought about by AM, as these innovative technologies have the potential to free composite production processes from the reliance on models and moulds. The current use of these tools adversely affects the industry because of their limited flexibility, their environmental implications (Musio-Sale et al., 2020), and associated costs (Peterson, 2021). In particular, moulds are not well-suited for complex designs due to the need for shape adjustments or significant investments in creating new moulds for each modification involved. An AM-oriented paradigm shift in the maritime industry could therefore help addressing longstanding challenges in the sector, making processes more versatile and open to extensive customisation possibilities.

In this perspective of innovation, it is important to critically review how the integration of AM can reshape not only the manufacturing processes but also the roles and experiences of the workforce and end-users within the industry. The interplay between technological advancements and human-centred issues of both workers and consumers warrants consideration. This paper will explore how AM technologies could redefine the roles of workforce in the maritime sector, examining the impacts on job roles, skills requirements, health and overall dynamics. Simultaneously, it will extend to the end-users, disclosing the influences on product customisation and associated user experience. Therefore, the aim of the research is to assess the current levels of implications that additive technologies have regarding human-centred issues within the maritime industry, evaluating the opportunities that could arise from this integration.

Initially, an extensive description of the search strategy and the articles' screening process is provided. Secondly, results regarding the impact of AM technologies on workers and end-users within the maritime industry are presented. Based on the findings, discussions are conducted, finally leading to the formulation of relevant conclusions.

METHOD

The systematic exploration for pertinent documents within the realm of the research focus was carried out by leveraging the comprehensive database of Scopus. In total, four clusters, each containing a series of keywords, were designed for the search: maritime industry, additive manufacturing, workers, and end-users.

The first phase of the search strategy was done through the combination of the conceived clusters. Subsequently, further articles were found by manually researching on Google Scholar.

The initial screening process involved reviewing the titles and abstracts of the articles, eliminating those deemed irrelevant to the research focus. Secondly, remaining documents underwent a more detailed examination through in-depth reading. After this, additional studies were identified through a cross-referencing phase.

A cataloguing and organisation process was applied to the selected articles by assigning identification keywords to each one. Keywords facilitated the efficient summarisation of the subjects addressed in each article, expediting the comparison activities. The identification of thematic connections among the different works enabled their grouping based on conceptual and thematic affinities.

RESULTS

Characteristics of Studies

During the exploration of pertinent studies, it was observed that the inclusion of the cluster related to the maritime sector yielded no results in the search. This suggests that the focus of this paper has not yet been extensively studied in the existing literature. Therefore, the articles selected address the research topic in broader terms, without expressly considering the target sector. Nevertheless, the selected studies offer valuable insights that could be suitable also for the chosen context, since the fundamental principles and concepts discussed are likely to have cross-sector applicability.

The first phase of the review identified a total of 1102 studies. Among those, after scanning titles and abstracts, 65 documents were assessed for meeting inclusion criteria. Finally, after the reading process and the cross-referencing activity, 34 studies were selected.

Out of the selected 34 studies, 23 specifically examine the implications for workers, delving into 15 studies exploring changes in required skills and six focusing on health-related aspects. One study pertains both skillsets and health. The remaining 11 studies delve into the theme of customisation and the product's relationship with end-users.

The study uncovered articles published from 2006 to 2023, with 21 of them published in the past decade.

Traditional Boatbuilding Techniques

Traditionally, the most widely used tool for the production of FRP boats is the mould, typically of the female type. In particular, the most prevalent lay-up techniques are 'hand lay-up' and 'spray-up' (Rubino et al., 2020).

In the 'hand lay-up' process (Andresen, 2001), reinforcement material is manually placed and then saturated with resin through the use of brushes or rollers. Adequate pressure is applied to ensure uniform resin distribution and eliminate any potential air bubbles.

A variation of manual lamination is the 'spray-up' method (Andresen, 2001), wherein a specially designed spray gun is used to simultaneously distribute resin and short fibres. Despite the relative simplicity of these processes, they demand significant manual labour and specialised expertise. As styrene vapours are released into the working environment (Säämänen et al., 1991; Lindgren et al., 2002), the direct handling of materials in open-mould processes poses health risks to operators. In fact, the European UP/VE Resin Association (2021) confirms the hazards related to occupational exposure to styrene. Workers exposed to such substance may encounter side effects, such as headaches, eye irritation, and respiratory disorders (Persoons et al., 2018).

In this context, the analysis of the currently employed traditional processes serves as a foundation for a better evaluation of additive technologies' impact. This overview not only facilitates the understanding of the opportunities presented by AM but also aids in identifying any potential aspects that need further interventions.

AM Impact on Workforce

Workforce Skillsets

A widespread integration of AM technologies into the maritime industry could profoundly redefine the roles of its workers. With the potential to transform production processes, these innovative techniques introduce new skillsets that must be cultivated among professionals through targeted education and training initiatives. AM techniques are highly reliant on digital processes which minimise the amount of manual labour involved in object creation (Garrett, 2014). By reducing needs for manual labour in tasks such as assembly (De Vere, 2013; Muita et al., 2015), manufacturing, and finishing (Tuck et al., 2007), the integration of 3D printing may lead to decreased reliance on workforce required (Ben-Ner and Siemsen, 2017). While automation could lessen demand for physically demanding manual jobs, it also presents an opportunity for upskilling workers to take on more technical and higher-skilled roles that leverage AM opportunities. Therefore, targeted training initiatives are important to help the workforce cultivate new digital skillsets demanded by these advanced production processes.

However, a significant challenge hindering the widespread adoption of AM is the limited knowledge of its technologies, capabilities and applications among the current workforce (Gao et al., 2015; Simpson et al., 2017). To fully leverage the opportunities brought by AM, professionals must develop a deeper understanding of both its technical processes and broader impacts on value chains (Williams and Seepersad, 2012). The importance of targeted education on AM is emphasised by Huang et al. (2013), who underscore its profound effects on both the environment and the economy.

The rapid proliferation of AM, driven by the increasing variety of materials and affordability of tools, as well as the potential for exploring new application areas, has led to a noticeable absence of guidelines for its standardisation within this dynamic field (Gao et al., 2015). As a result, despite the transformative potential of AM, the predominant focus in today's education remains centred on traditional production techniques, neglecting these emerging technologies (Kriesi et al., 2014).

To meet the evolving demands of the AM-enabled market, workers require not only familiarity with digital design tools but also expertise in operating the new equipment (Roos and Fusco, 2014). Practical learning and hands-on experience with 3D printing are crucial, as they foster creativity while enhancing comprehension of workflows (Lacey, 2010). Introducing emerging designers to AM from an early stage through university courses or industry training can instill a "think additive" mindset characterised by innovative problem-solving and exploitation of the technology's design freedom (Minetola et al., 2015).

Several recommendations have been proposed with the aim of significantly promoting the depth and breadth of AM knowledge through educational initiatives. In particular, the 2009 Roadmap for Additive Manufacturing called for the development of specialised training programs and university with the aim of generating a broader awareness and enthusiasm for these technologies within society (Bourell et al., 2009). More recently, industrial gatherings like the 2015 National Science Foundation workshop brought together professionals to discuss priorities for the AM workforce. Key takeaways emphasised building fundamental engineering and materials science comprehension, as well as proficiencies in problem-solving, design leveraging AM possibilities, and collaborative ideation (Huang et al., 2015). Despeisse and Minshall (2017) outlined a series of guidelines to enhance AM skills and knowledge among professionals:

- recognise the diversity and value of AM technologies;
- Use new tools and approaches for designing products that are compatible with AM processes;
- understand the processes and materials involved;
- stay updated on the evolving nature of AM technology;
- provide a balance of general and specialized education;
- support both students and workers for the demands of the AM industry.

Workforce Health and Safety

AM's potential impact on operators extends to health and safety concerns. While AM technologies offer several advantages, the literature also tends to highlight potential occupational health risks associated with 3D printing. Various studies have reported cases of health problems experienced by workers operating 3D printers. AM processes in fact can release ultrafine particles and volatile organic compounds into the air (Chan et al., 2018). Central nervous system damages and respiratory symptoms such as asthma and irritation have been reported by industries that employ AM (Mohammadian and Nasirzadeh, 2021). In particular, As emphasised by Saliakas et al. (2023), the greatest risk of exposure to toxic substances was identified at the initiation of the extrusion process and during cleaning activities. Studies have found that working extensively with 3D printers, more than 40 hours per week, is significantly associated with an increased risk of respiratory diagnoses (Chan et al., 2018).

To mitigate these occupational health hazards, various guidelines have been proposed. Important control measures include substitution, isolation, proper ventilation of workplaces, and the wearing of protective equipment (Rim, 2023). In addition, McDonnell et al. (2016) stress the importance of using carbon filters to reduce harmful emissions. A written standard operating procedure outlining health and safety policies in the workplace is also recommended (Randolph, 2018). Concerning styrene vapour concentrations, measured in parts per million (ppm), the American Conference of Governmental Industrial Hygienists (ACGIH) (ACGIH, n.d.) established the threshold limit value (TLV) for occupational exposure. The maximum allowable exposure level for an 8-hour workday (TWA: time-weighted average) is established at 10 ppm. For brief durations (STEL: short-term exposure), typically 15 minutes, the permissible concentration is set at 20 ppm.

While many studies warn of potential risks, some research highlights how AM could potentially reduce harmful chemical exposures compared to conventional manufacturing (Garrett, 2014). FDM processes in particular have been deemed safe and non-toxic (Masood, 2007).

AM Impact on End-Users

The demand for customisation continues to grow among consumers who seek products personalised to their unique needs and preferences. In this evolving landscape, 3D printing could play a pivotal role, advancing the industry to meet end-users' requests (Dean and Pei, 2012; Liu and Yang, 2023). In this regard, Weller et al. (2015) state that AM proves to be particularly beneficial in settings where there's a high demand for tailored products, adaptable manufacturing processes, and intricate designs.

Several findings in the literature indicate that extensive customisation possibilities can redefine the relationship between products and consumers. Brun and Karaosman (2019) outline a positive correlation between the extent of customisation and the perceived value of products within the yacht industry. Moreover, the study emphasises that companies offering more exclusive products tend to encourage greater levels of customisation and customer engagement. A stronger emotional connection may form between customised products and their owners (Campbell and Bernabei, 2017; Liu and Yang, 2023). When preferences can be reflected in product design, users feel the item is well-suited for their specific needs (Nurkka, 2013). Consumer participation in co-design can also boost perceived value by giving individuals influence over product attributes that matter most to them (Schreier, 2006; Merle et al., 2009).

From this standpoint, companies may choose to facilitate consumer input in the design process (Valenzuela et al., 2009). Rather than developing fully-formed designs alone, designers could establish initial design frameworks for end-users to personalise according to their needs (Campbell and Bernabei, 2017).

Given the renowned global reputation of the yacht industry for its extensive customisation practices (Bionda and Ratti, 2017), these strategies could seamlessly align with yacht design processes, potentially enhancing the interaction between customers and design studios. In this context, Hu (2013) emphasises the pivotal role of AM as a facilitator for advancing co-design processes.

DISCUSSION AND CONCLUSION

The results of this literature review provide valuable insights into how additive technologies could reshape human roles within the maritime industry, specifically examining how they could affect workers and end-users. While the findings indicate AM presents advantages such as improved flexibility and opportunities for customisation, there are also significant changes and impacts that require consideration to ensure successful implementation.

A key gap of the current literature is the lack of papers that specifically explored applications and experiences within the maritime sector. Most of the retrieved studies evaluated implications in broader contexts. To better guide 3D printing adoption in this target area, more empirical research conducted collaboratively with maritime stakeholders is needed.

On the workforce front, it is evident skills requirements will evolve significantly as processes become more digitally oriented and automated with AM integration. While several studies (Garrett, 2014; De Vere, 2013; Muita et al., 2015; Tuck et al., 2007) indicate that automation may decrease demand for physically demanding manual labour, it presents an opportunity to upskill workers into higher value roles. However, the literature shows AM knowledge and expertise remains limited among current professionals. Large-scale training initiatives collaborating closely with both educational institutions and industry will be crucial to cultivate the new digital and technological skillsets demanded by AM. Standards and guidelines outlining education frameworks with a balanced mix of general and specialised AM training should also be developed.

Although the topic of AM occupational risks is still a matter of debate within the literature, with some papers emphasising AM's safety (Garrett, 2014; Masood, 2007), health and safety standards specifically targeting potential hazards arising from AM material emissions must be established. Accordingly, the studies conducted by ACGIH (n.d.) represent a significant contribution. Regular review of these policies based on the latest research evidence will ensure they continuously safeguard worker wellbeing as new 3D printing equipment, materials and processes emerge. Preventive control measures informed by robust risk assessments should minimise exposure risks to support the long-term health of AM operators. Furthermore, the high degree of automation enabled by AM, alongside its capability to decentralise production (Attaran, 2017), could enable the creation of isolated production environments that minimise the need for direct worker involvement. In that light, future studies should delve into such implications.

For end-users, AM profoundly enables greater customisation possibilities that have long been important to the maritime industry. This aligns well with growing consumer demands for tailored products that better meet individual preferences and needs. In this context, valuable findings regarding the yacht industry are provided by Brun and Karaosman (2019), who found a positive correlation between customisation levels and perceived product value, suggesting AM could enhance customer engagement and satisfaction in yacht design. Enhanced co-design and engagement strategies allowing users more input over product attributes could further strengthen the relationship between manufacturers and customers. In this perspective, future studies should focus on developing a framework for advancing end-user engagement in the design process so that customisation possibilities offered by AM are maximised.

The present research was conducted within the NEMO project, initiated by the Design Department of Politecnico di Milano in collaboration with PNRR MICS (Made in Italy Circolare e Sostenibile). Since the project is addressing yacht flexible customisation through 3D printing, the results gathered in this manuscript, while broader than the core focus of NEMO, could help guide the research to consider these cross-cutting human-centred aspects in applying AM for yacht construction. Overall, continuous assessment of social impacts on both the workforce and end-users will be important to proactively address challenges and maximise benefits. With prudent navigation and management of these considerations, AM is well positioned to shape a prosperous future for the maritime industry through highly tailored products and experiences.

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