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Potential for absolute sustainability of Wire-Arc Additive Manufacturing: A boat propellers case

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ABSTRACT

The industry sector has high carbon emissions with a large contribution stemming from metals manufacturing. There is an increasing interest in additive manufacturing (AM) as a manufacturing technique for lean manufacturing and circular economy (CE), but can it become environmentally sustainable? We propose a holistic framework to investigate future resource-use efficiency and environmental impact potentials of AM for metal object production and demonstrate it on an industrial case. The framework has shown potential in highlighting trade-offs in choosing the best CE strategies and manufacturing technology. The most promising CE strategies, in this case, were improved propulsive efficiency and closed-loop recycling.

1. Introduction

Over the previous decade, there has been a steep increase in interest in additive manufacturing (AM) by companies and researchers within the manufacturing sector for its potential in product shape complexity, lead-time, and resource-use reduction [1,2]. Companies and researchers have recognized the importance of environmental sustainability from a product life cycle and circular economy perspective [2] amongst other due to the industry sector contributing to 30% of total annual global CO_2 emission (i.e., 12 Gt) [3]. A significant contributor is steel production, which in 2019 was about 3 Gt CO_2 emission, corresponding to 8% of the yearly worldwide CO_2 emissions [3]. Circular economy aims to maintain the value of materials for as long as possible. In this study, the aim is to assess how Additive Manufacturing (AM) and circular economy strategies can influence flows and stocks of primary and secondary materials used for a product fabrication, and their impact in the future taking an absolute sustainability perspective.

In this study, the focus is on a specific product, a boat propeller with the diameter of 2 m for use in fishing vessels. This is assumed to be produced using casting (as conventional manufacturing technique) or multi-material Wire-Arc Additive Manufacturing (WAAM). The latter is an AM technique in which layers of different metallic wires are deposited and an electric arc is used as a heat source to perform layer-by-layer welding [4]. WAAM has become increasingly popular for producing large metallic spare parts requiring complex shape fabrication and topology optimization, enhanced by the multi-material use [4], and depending on the supply chain can potentially reduce typical lead times up to about 75% (see Table S.2 in Supplementary materials (SM)).

2. Methodology

Fig. 1 illustrates a scheme of the framework used in this study, which is based on the combination of dynamic Material Flow Analysis (MFA) with Absolute Environmental Sustainability Assessment (AESA) to evaluate the potential application of multi-material WAAM under Circular Economy (CE) strategies [5,6]. Previous works emphasized the need of a more holistic approach to assess manufacturing for sustainability by combining concepts of Life Cycle Engineering and Industrial Ecology [7,8].

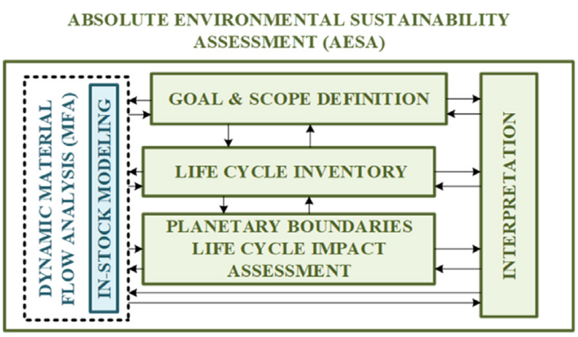

Fig. 1. Holistic framework to assess product environmental impact (in green) and resource-use efficiency (in blue). The arrows highlight the iterative nature of the methodology.

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2.1. Goal and scope definition

To quantify potential changes in the environmental impact that WAAM can bring to boat propeller manufacturing, different scenarios for the global demand of boat propellers for fishing vessels, which currently are produced with bronze alloy casting, were investigated. Table 1 briefly describes each scenario and the circular economy (CE) strategies considered. The CE strategy applied in each scenario is decided based on: (i) manufacturing process design possibilities and (ii) likely circular economy strategy application.

Table 1
Scenario definition and addressed circular economy (CE) strategies using the framework defined by Kirchherr et al. [10]. A detailed explanation of assumptions is in Table S.2 in SM.

Scenario	1 (BAU 1)	2 (BAU2)	3 (WAAM)
	Business-as- usual 1 (BAU1) with casting and open-loop recycling	Business-as-usual 2 (BAU2) with casting and closed-loop recycling	Multi-material WAAM gradually substitutes casting from 2020 to 2050 (annual increase rate of 1.5%)
Circular Economy strategies	RECYCLE: process metal for other products line (open-loop)	RECYCLE: process metal for the same product line (closed-loop)	RETHINK: 9 years prolonged lifetime REDUCE: fuel consumption reduced by 0.1% RECYCLE: process metal for other/ same product line

The functional unit (FU) used in the study was defined as *"global average propulsion of average fishing vessels from 2010 to 2050"*. "Average" considers the propulsion of fishing vessels in year 2015, with an average fishing vessel of 100 tons and a boat propeller of roughly 2 tons (see Supplementary materials (SM) chapter S.2).

The temporal and geographical scope were set to be from 2010 to 2050 and global, respectively. Fig. 2 illustrates the generic cradle-to-grave system boundaries for the fishing vessels propeller life cycle. For scenarios 1 and 2 (BAU1, BAU2) boat propellers are produced by casting of Al-bronze alloy (see in SM in Fig. S.1 and S.2), and for scenario 3 (WAAM) two alloys: steel S355 and inconel 625 are utilized (see Fig. S.3 in SM). System expansion was applied whenever there were multifunctional processes (see Fig. 2) [9].

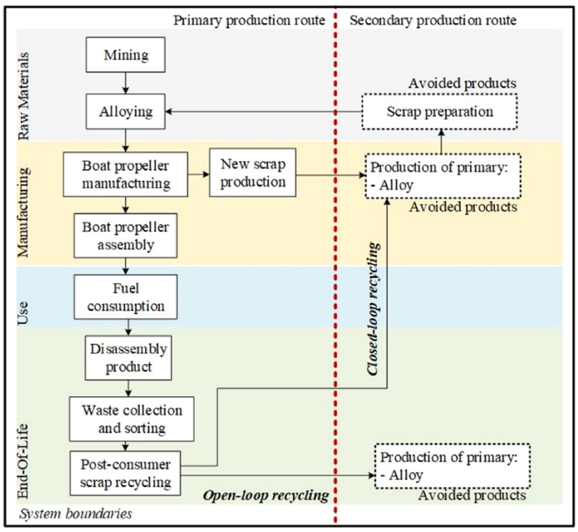

Fig. 2. System boundaries for fishing vessels propellers life cycle. The boxes with the dotted boundaries represent system expansion. Transportation, fuel production and electricity use are not represented, but they are considered in the AESA model.

SimaPro9.4.0.2 and ecoinvent3.8 consequential were employed as software and database in the study, respectively. The latter was chosen as it is recommended for predictive studies [9].

The four main assumptions of the study are: (1) constant annual increase rate in the boat propellers market; (2) fixed composition of the grid mix for electricity generation; (3) constant recycling yields over time; and (4) increased propulsive efficiency and extended lifetime of propeller in the WAAM scenario thanks to reduction of cavitation erosion damage and increased hardness (see Table S.2 in SM). Moreover, the study considers that the boat propeller is finished and assembled into a fishing vessel, and the metal chips from milling are collected for open or closed-loop recycling.

2.2. Dynamic material flow analysis (MFA)

In the last decade, there has been extensive research on historical and prospective dynamic Material Flow Analysis (MFA) [5]. Dynamic MFA is a tool commonly used in life cycle engineering where its in-stock modelling approach allows to assess flows and stocks of materials for a specific system. This study's intended use is to investigate how the gradual introduction of WAAM will affect the worldwide demand for fishing vessels boat propellers. The focus is mainly on the assessment of the type and amount of primary and secondary materials, and the effects of closed- or open-loop recycling on the scrap stocks (see details in the SM in the chapter S.5). In this study, exogenous flows (e.g., primary bronze from global market) were calculated in connection to flows with annual constant value (e.g., new built boat propellers) and recycling yields from the literature [11] (see Table 2) through mass-balance equations modelled in Python 3.9.11.

Table 2
Recycling yields from the literature [11]. Y_{NS} = yield recycled new scrap (assumed to be 100%); Y_{PC} = yield recycled post-consumer scrap; Y_{IS} = yield secondary material as metal production input.

Alloy	Y_{NS} value [%]	Y_{PC}	Y_{IS}
Aluminium bronze	100	45	35
Steel (355)		53	42
Inconel 625	100		47.5
Stainless steel		53	

2.3. Absolute environmental sustainability assessment (AESA)

The concept of absolute sustainability introduces the need to develop a prosperous society in respect of the Earth's carrying capacity [6]. The main advantage for decision-makers is that this holistic framework simultaneously considers several planetary environmental pressures and provides measurable targets, which can be used to take actions. The PB-LCIA methodology developed by Ryberg et al. [12] was applied to the calculated dynamic material flows for this study to predict the impact change with the introduction of WAAM to support the future global demand of boat propellers for fishing vessels. In this study, only one of the eight impact categories included in the PB-LCIA is presented. This is "*Climate change – CO_2 concentration*", which represents the CO_2 emissions from the product system. The occupied safe operating space for the anthropogenic activities linked to the life cycle of boat propellers for fishing vessels was determined with two different sharing principles [12]: Gross Value Added (GVA) (see eq. S.5 and S.5a in SM), and grandfathering (see eq. S.6 in SM). The first principle is based on the GVA for propellers for fishing vessels manufactured with either casting or WAAM in proportion to the total global gross value added. The second principle is based on the current contribution to environmental impacts from the global demand for boat propellers for fishing vessels.

2.4. Sensitivity analysis

A simple sensitivity analysis was performed for: (i) a 25% increase in the annual substitution rate of WAAM (from 1.5% to 1.88%), (ii) a 25% reduction of the lifetime extension for boat propellers produced with WAAM, and (iii) an optimized propulsive efficiency for the boat propeller manufactured with WAAM. The first two were one-at-time parameter perturbations, and the third is a scenario sensitivity analysis. More details on the equation used to determine the sensitivity of the model are available in Supplementary Information chapter S.6.

3. Results and discussion

Fig. 3 shows the cumulative material flows and stocks from 2010 to 2050 and the annual evolution of the three scenarios for the future production of fishing vessels boat propellers. In scenario BAU2 (Fig. 3b1) it is noticed that 4/5 of the secondary bronze is provided by the recycled bronze thanks to closed-loop recycling. Additionally, Fig. 3b2 shows that the scrap stock and the secondary bronze follow a similar trend - when the scrap stock from dismissed boat propellers is not sufficient, scrap from the global market is sourced. Fig. 3c1 illustrates that with the introduction of WAAM there is an overall reduction in materials needed for the casted boat propeller. The gradual substitution rate of WAAM is relatively low (1.5% increment per year), nevertheless the values for “Manufacturing”, “New built”, “Increase in-use” and “Dismissed” are a couple of kilotons lower relative to BAU1 and BAU2. This is linked to the advantage of the prolonged lifetime of the boat propellers produced with multi-material WAAM (see Table 1), which contributes to a reduction in the demand for new spare parts. Additionally, the demand of bronze in the WAAM scenario is reduced by roughly 8% (see Fig. 3a). All of that demonstrates the potential of WAAM in the reduction of the overall need of materials to satisfy the worldwide demand of fishing vessels boat propellers. Furthermore, it is worth to mention that the cumulative losses of metals in this study are about 80 kt in all three scenarios. This reflects the material recycling yield, which is based on the literature is assumed to be about 50% (see Table 2). It is also worth to mention that in the WAAM scenario the recycling of the boat propeller into stainless steel represents a case of down-cycling as stainless steel has a lower value than inconel.

Fig. 4 shows environmental impact of the considered scenarios (“Life cycle”) and for the separate stages, “Material&Manufacturing”, “Use”, and “Disposal” for the impact category “*Climate change – CO_2 concentration*”. Table S.1 in the SM reports the characterized results also for all the other PB-LCIA impact categories. Fig. 4b shows that the global propulsion of boat propellers for fishing vessels in the WAAM scenario never exceeds the planetary boundary (PB) for "*Climate change* - CO_2 *concentration*", but the life cycle does after 2035. BAU 1 and 2 instead, go beyond the PB ten years earlier, in 2025. In addition to that, Fig. 4b shows that WAAM impact score has a slower incremental increase from 2020 to 2050 compared to the other two scenarios. This is due to the fact that the impact score of propulsion in WAAM is about one order of magnitude smaller than BAU1 and BAU2 (see Table S.1 in SM). All of this illustrates that the circular economy strategy applied to the boat propeller produced with WAAM (i.e., reduce) lead to evident benefits when GVA is taken into account.

Furthermore, it is interesting to notice that negative impact scores are connected to disposal in Fig. 4. This is due to modelling approach that consider avoided primary material thanks to recycling of post-consumer scraps. The difference in the results between the two sharing principles stems from the fact that their downscaled share of safe operating space (SoSOS_{PB}) differs by about 1 to 2 orders of magnitude. This illustrates problems of using grandfathering for a new technology like WAAM.

The two sensitivity analyses considering one parameter (i.e., substitution rate and product lifetime extension) showed to be insignificant. In contrast, further fuel efficiency optimization during the use of the boat propeller showed to be relevant when Gross Value Added is considered (see SM in chapter S.6). As the study presents several assumptions, and future technological developments for recycling or energy sources were not taken into account, it is recommended to test the model further with a more extensive sensitivity and uncertainty analysis.

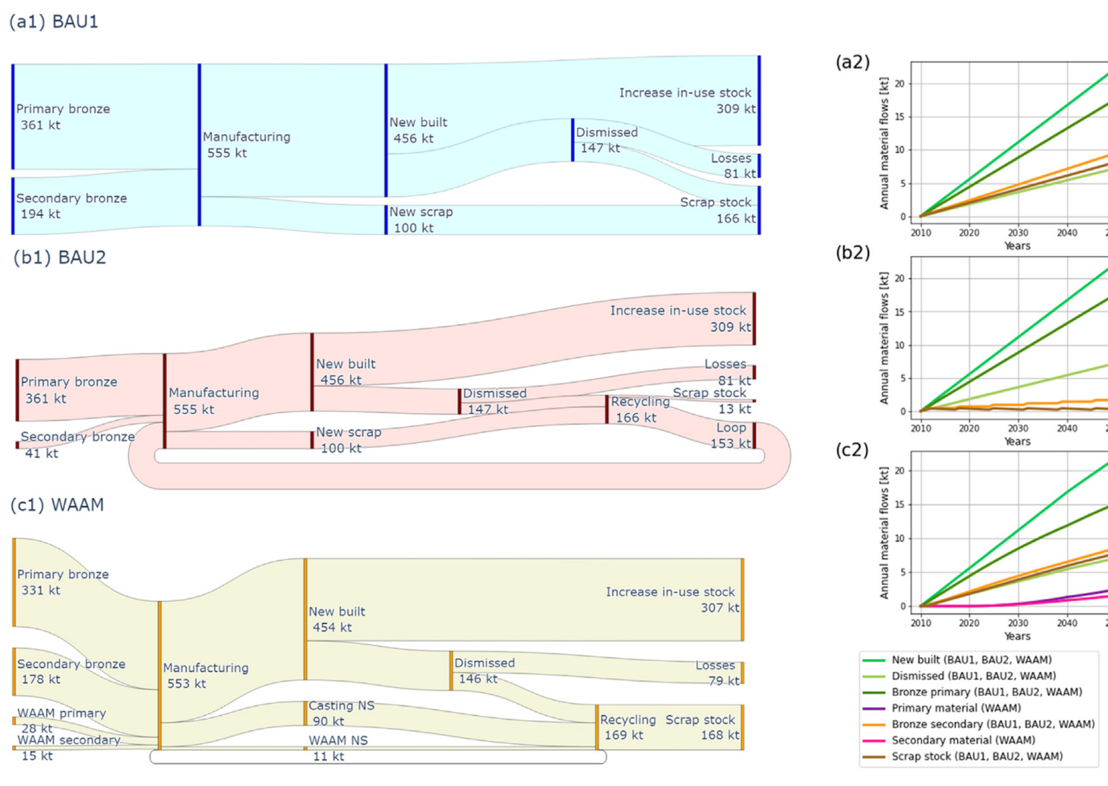

Fig. 3. On the left side there are Sankey diagrams with cumulative values of material flows and stocks from 2010 to 2050, and on the right side are line-graphs showing the estimated yearly evolution of the material flows and demands for boat propellers for fishing vessels for the analysed scenarios. (a1–2) Business As Usual (BAU1), (b1–2) Business As Usual 2 (BAU2), and (c1–2) Wire-arc Additive Manufacturing (WAAM). “Casting NS” and “WAAM NS” are bronze and inconel new scrap, respectively. “Increase in-use stock” considers the net increase of in-use new produced boat propellers.

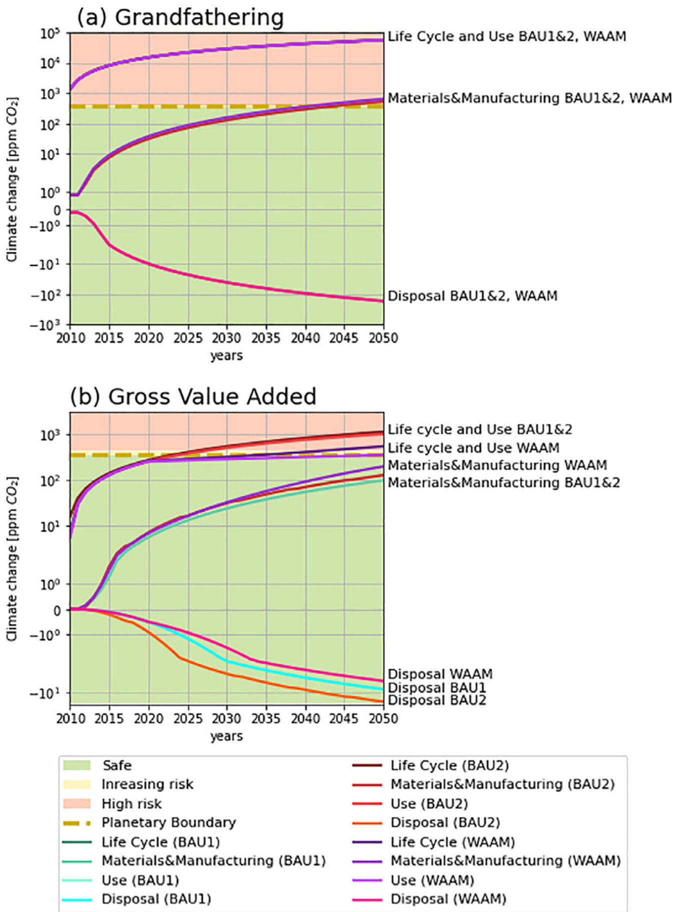

Fig. 4. Absolute Environmental Sustainability Assessment (AESA) for the global demand for fishing vessels boat propeller, derived from dynamic material flow analysis from 2010 to 2050 using (a) grandfathering, and (b) Gross Value Added (GVA) combined with PB-LCIA method [12] for *"Climate change - CO_2 concentration"*. The green area represents the "safe" space in which the product system is absolute sustainable. The yellow section ("Increasing risk") is the area of uncertainty related to the product system sustainability. The red area expresses "high risk" and the product system is very likely not absolute sustainable. The golden dotted line represents the planetary boundary for the global demand for fishing vessel propellers. The graphs show the "Materials&Manufacturing" stage, the "Use" stage, the "Disposal" stage and the sum of the three ("Life cycle") for each of the three scenarios. Results are reported in logarithmic scale.

4. Conclusions

Overall, this holistic framework showed the potential to aid decision-making for companies to be used as a support tool for holistic production planning by avoiding burden-shifting and highlighting trade-offs in choosing the best circular economy strategies and manufacturing technology. In particular, the circular economy strategy "rethink" (i.e., product extended lifetime) showed potential for resource-use efficiency, while "reduce" (i.e., improved propulsive efficiency) appeared to lead to significant advantages in terms of environmental impact for the planetary boundary *"Climate change - CO_2 concentration"*. However, none of the scenarios resulted to be absolute sustainable for the impact category considered throughout the whole study. The closed-loop recycled scrap for the conventional boat propeller will be enough to cover the majority of the demand for secondary material in BAU2. Thus, it is recommended to implement circular economy strategies that could incentivize closed-loop recycling (i.e., take-back program). Lastly, the study also demonstrated that the choice of sharing principle is challenging and is relevant to consider when drawing conclusions in this case. Thus, the authors recommend considering several sharing principles when performing Absolute Environmental Sustainability Assessment (AESA).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cirp.2023.04.034.

References

[1] Ford S, Despeisse M (2016) Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production* . 137/1573–1587.
[2] Saade MRM, Yahia A, Amor B (2020) How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. *Journal of Cleaner Production* . 244/118803.
[3] Krishnan M, Samandari H, Woetzel J, Smit S, Pacthod D, Pinner D, Nauclér T, Tai H, Farr A, Wu W, Danielle I (2022) The net-zero transition: what it would cost, what it could bring. *McKinsey Global Institute*.
[4] Taşdemir A., Nohut S. (2020) An Overview of Wire Arc Additive Manufacturing (WAAM) in Shipbuilding industry. Ships and Offshore Structures. Taylor and Francis Ltd. 1–18
[5] Wang P, Ryberg MW, Yang Y, Feng K, Kara S, Hauschild M, Chen WQ (2021) Efficiency stagnation in global steel production urges joint supply-and demand-side mitigation efforts. *Nature Communications* 12(1):1–11.
[6] Ryberg MW, Owsianiak M, Richardson K, Hauschild MZ (2018) Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework. *Ecological Indicators* . 88/250–262.
[7] Kara S, Hauschild MZ, Sutherland J, McAloone T (2022) Closed-loop systems to circular economy: a pathway to environmental sustainability? *CIRP Annals* 71 (2):505–528.
[8] Hauschild MZ, Kara S, Røpke I (2020) Absolute sustainability: challenges to life cycle engineering. *CIRP Annals* 69(2):533–553.
[9] European Commission Joint Research Centre. *ILCD Handbook-General guide on LCA-Detailed guidance*, Institute for Environment and Sustainability, . https://doi.org/10.2788/94987.
[10] Kirchherr J, Reike JD, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. *Resources, Conservation and Recycling* . 127/221–232.
[11] United States Geological Survey. *Mineral commodity summaries 2020: U.S. Geological Survey*.
[12] Ryberg MW, Owsianiak M, Clavreul J, Mueller C, Sim S, King H, Hauschild MZ (2018) How to bring absolute sustainability into decision-making: an industry case study using a Planetary Boundary-based methodology. *Science of the Total Environment . 634*/1406-1416.