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Research article

# A LCA and LCC analysis of pure subtractive manufacturing, wire arc additive manufacturing, and selective laser melting approaches

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ABSTRACT

The development of sustainable manufacturing solutions is gaining attention in the manufacturing sector due to increased awareness about climate change and the formulation of stricter environmental legislation. Sustainable manufacturing involves the development of solutions that are environmentally friendly and cost-effective at the same time. Considering the opportunities and limitations of metal subtractive and additive manufacturing approaches from a sustainability perspective, this study aims to compare the environmental impact and production costs associated with the manufacture of a marine propeller using pure subtractive CNC milling along with additive Wire arc additive manufacturing (WAAM) and Selective Laser Melting (SLM) approaches. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are used to quantify the environmental and economic impacts, respectively for each manufacturing approach. Based on the LCA and LCC models formulated, and the input data collected, the WAAM approach is observed to be the most environmentally and cost-efficient approach for the marine propeller analyzed. WAAM shows an environmental impact about 2.5 times and 3.4 times lower than pure CNC milling and SLM approaches, respectively mainly due to its better material and energy efficiencies. The effect of key variables on the environmental impact and production cost such as raw material, electricity, and post-processing parameters like a material allowance for finish machining and cutting velocity is also studied to suggest the parameters ensuring sustainable performance for a particular approach. WAAM is seen to be the most economical and ecological option for a post-processing material allowance under 4 mm and the finish machining velocities below 96 m/min. Additionally, an uncertainty assessment using the Monte Carlo analysis method is also performed to give a probabilistic range of environmental impacts and production costs considering the input data uncertainties for each approach. The methodology used in this study can be applied to other additive manufacturing processes. This study can be of potential help to AM practitioners in decision-making on selecting the most sustainable approach for manufacturing their products.

## 1. Introduction

Climate change is a serious issue of concern nowadays due to the rising atmospheric temperatures caused by increased toxic emissions. The manufacturing sector, which is a resource and energy-intensive sector, is a significant contributor to the increased environmental emissions. However, it is also a key contributor to the economy and improving the standard of living of human society. For instance, in the context of the European Union (EU), presently the manufacturing sector accounts for 15 % of its gross domestic product (GDP) [1], absorbs nearly 26 % of the final energy consumption [2], and is responsible for about 23 % of the total greenhouse gas emissions [3]. Hence, there is a need to reduce the environmental emissions of the manufacturing sector by developing and adopting more sustainable manufacturing practices. According to the United States Environmental Protection Agency, sustainable manufacturing involves the manufacture of goods using economically sensible approaches that decrease the adverse impacts on the planet while simultaneously preserving natural resources as well as energy [4]. According to Rashid et al. [5] sustainable manufacturing can be achieved by the following four primary strategies: 1) Waste

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minimization which includes using the material in a lower amount, creating durable products, preventing waste generation, using less toxic materials; 2) Material efficiency (corresponding to energy efficiency) that focuses on decreasing the consumption of primary raw materials without compromising the product functionality; 3) Resource efficiency that attempts for efficient use, reduction of flow and utilization of natural resources: and 4) Eco-efficiency focussing on the delivery of cost-effective goods and services that satisfy the customer needs while progressively reducing the resource consumption and environmental impacts.

Conventional subtractive manufacturing technologies such as CNC milling are widely used in the fabrication of metal parts due to their advantages such as the ability to achieve better dimensional accuracy, higher precision, higher repeatability, smooth surface finishes, better reliability, and technological maturity, among others [6]. However, for manufacturing complex geometries, these conventional approaches require large amounts of material removal resulting in lower material efficiencies and negatively affecting their sustainable manufacturing potential. For instance, in the manufacturing of some aero engine parts, conventional processes exhibit poor material efficiencies ranging between 5 % and 17 % [7]. In contrast to the conventional subtractive processes, metal additive manufacturing (AM) processes can save a lot of material due to their freedom to fabricate very complex geometries. Matured AM processes, such as Powder Bed Fusion (PBF) type of additive manufacturing, selectively melt and fuse metal powders using a laser and can be an effective material-efficient manufacturing approach for complex parts leading to the generation of lower material wastes. PBF processes have found applications in high-value-added sectors like aerospace, automotive, and biomedical implants [8]. However, these PBF processes have higher energy requirements than conventional subtractive processes [9]. From a commercial perspective, PBF processes need more expensive machine tools than conventional processes, need post-processing operations to achieve the desired surface finish, and have slower build rates leading to high production times [10]. A novel directed energy deposition (DED) type AM process wire arc additive manufacturing (WAAM) is emerging in the past few years, where a metal wire is melted using an electric arc and deposited layer-by-layer. Compared to SLM, WAAM has a higher build rate (50–130 g/min) than AM processes using lasers (2–10 g/min) [11]. Owing to this advantage, WAAM has found several applications in building large-scale metal parts, especially in the shipping industry [12]. Additionally, WAAM requires lesser expensive machine tools and has open architecture where the user can combine hardware parts of different brands [13]. However, WAAM has lower dimensional accuracy and poor surface and hence requires finish machining [14].

It can be inferred from the above discussion that both subtractive and additive approaches have their own merits and demerits from a sustainable manufacturing perspective. Traditional subtractive manufacturing could be cost-efficient but not material-efficient, particularly in the case of complex geometries. SLM can exhibit better material-efficiency but has lower energy and cost-efficiency, compared to the subtractive approach. On the other hand, WAAM can have better cost-efficiency but worse material-efficiency than SLM. Hence, a trade-off between material, energy, and cost efficiencies is seen while qualitatively analyzing the CNC machining, SLM, and WAAM approaches. To ensure a sustainable manufacturing process selection, it is necessary first to quantitatively evaluate their environmental burdens and economic viability in manufacturing industrial products. Therefore, the main objective of this study is to compare the environmental as well as economic performance of the pure subtractive approach i.e., CNC milling, and two additive approaches i.e., SLM and WAAM in the manufacture of a complex industrial product – a steel marine propeller. This paper has been structured as follows: Section 2 reviews the existing literature on sustainability assessments of conventional and additive approaches. In Section 3, the manufacturing of marine propellers using CNC milling, SLM, and WAAM is reviewed. The environmental and economic assessment methodology used in his paper has been explained in Section 4. Section 5 presents the case study involving ecological and economic assessment of the marine propeller. In Section 6, the influence of different process variables on the sustainability of a process is studied. Additionally, an uncertainty assessment is done, and the limitations of the study are discussed. Finally, Section 7 presents the conclusions of this study and the guidelines for future research.

## 2. Literature review

Evaluating the environmental impacts of metal AM processes using LCA methodology has been gaining momentum in the last few years. Saade et al. [15] performed a systematic literature review to study the application of LCA in AM technology. It was reported in this study that the powder bed fusion (PBF) category of AM processes like Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Electron Beam Melting (EBM) have gained more attention in comparison to Directed Energy Deposition (DED) type of AM processes like WAAM. Kellens et al. [16] developed parametric models to predict the environmental impact of parts made up of polyamide powders of grade PA2200 and PA3200GF. Studies assessing the environmental impacts of the SLM process in the manufacture of a variety of commercial products such as aerospace components [17], automotive components [18,19], Al—Si impeller [20], stainless steel hydraulic valve [21], and washer [22], and Inconel 718 aeronautical turbine blade [23], among others, have been reported. Similarly, the environmental burdens of the EBM process in manufacturing products like Ti6Al4V aeronautical turbines [24], biomedical devices like femoral stems [25] and femoral components [26] of a knee implant, and some cylindrical mechanical components [27,28], among others have been assessed.

However, DED-type processes such as WAAM have received comparatively lesser attention than the SLM process, as far as environmental assessments are considered. Some studies assessing the material and energy consumption of WAAM have been reported [29,30]. Priarone et al. [30] assessed the energy demand and cost of WAAM in the production of an aluminium frame, steel beam, and titanium bracket. WAAM was seen as a more material-efficient and energy-efficient approach than CNC machining for all three products. However, it was seen to be the most economical option for aluminium and titanium components but not for steel beam. The machining approach was observed to be the most economical option for the steel beam due to its significantly lower manufacturing times. Campatelli et al. [29] compared the energy and material efficiency of integrated WAAM-finish machining and pure subtractive machining approaches in manufacturing a steel airfoil. Compared to the pure subtractive approach, the WAAM approach demonstrated a material reduction of 60 % and energy saving of 34 % but increased the processing time by 26 %. Hence, a trade-off between productivity and energy efficiency is seen in the case of the WAAM approach. Some case studies performing an LCA of WAAM products were also reported in the literature [31–33]. Bekker and Verlinden [31] compared the cradle-to-gate environmental impacts of WAAM, CNC milling, and green sand casting approaches in the manufacturing of 1 kg stainless steel 308 l product. WAAM was seen to be more eco-friendly than green sand casting by a small margin (5 %) whereas compared to the CNC milling approach, WAAM showed an impact reduction of 35 %. However, this study did not include the effect of post-processing operations such as machining operations used to achieve final dimensions and tolerances in WAAM. Only the sand blasting process that removes the oxidation layers on the weld surface was included in this study. Shah et al. [33] carried out a comparative ecological assessment of WAAM and hot rolling in manufacturing of carbon steel and stainless steel I section beams. The carbon and stainless-steel beams produced by WAAM reported 7 % and 24 % lower $CO_2$ emissions, respectively than their hot-rolled counterparts, due to better material efficiency achieved by WAAM. Like the previous study, this study also used sandblasting as the finishing process. However, for mechanical components like the airfoil [29] or the marine propeller considered in this study that are fabricated by WAAM, finish machining operations are required in post-processing to achieve final dimensions and surface finish. Kokare et al. [32] compared the environmental impact and production cost of a high strength low alloy steel (ER70) flat wall fabricated by WAAM, SLM, and pure CNC milling. Face milling and surface grinding operations were used in the post-processing of the as-built WAAM wall. It was seen that WAAM is the most ecological and economical option only in the cases of walls with complex curvature profiles, where the material efficiency for CNC milling processes is <11 %. However, this study involved a very simple geometry of little practical use, and more studies involving complex real-life products are required to further verify the findings of this study. Based on the literature review, the following research gaps are realized:

(i) WAAM has promising material and energy-saving potential but needs post-processing operations that can affect its cost and productivity. Therefore, its environmental and economic potential must be assessed quantitatively including the effect of post-processing operations.
(ii) The majority of the existing studies assess only the environmental dimension of sustainability, ignoring the economic dimension. Fewer studies have focussed on the economic potential of SLM [22,32,34] and WAAM [30,32], in addition to their environmental potential. The cost of a manufacturing process is an important sustainability dimension and a decisive criterion for the decision-making on process selection by manufacturers. Hence, there is a need to study the economics of WAAM adoption more thoroughly.
(iii) The majority of the existing studies are carried out under static scenarios of variables namely materials, process parameters, and product geometry, and their results are highly sensitive to these variables. The variation or uncertainty in these variables can affect the results significantly. Hence, the effect of uncertainties/variations in these variables on the environmental and economic impact should also be studied. Additionally, more studies involving different materials, processing parameters, and product geometries should be studied to effectively understand the economic and environmental potential of WAAM.

Therefore, the main objective is to carry out a comparative environmental and economic assessment of WAAM (including its post-processing operations), SLM, and pure CNC milling approaches in manufacturing a real-life complex product: a marine propeller composed of a high strength low alloy steel (ER70). Furthermore, this study also analyses the effect of variation in raw material type, electricity mix, post-processing material allowance, and cutting velocity, and suggests under what conditions a particular manufacturing approach is ecological, as well as economical. The effect of uncertainty in the input parameters is also studied statistically using the Monte Carlo uncertainty analysis method, which provides a probable range of environmental and economic impacts for each approach, covering a broader range of "what-if" scenarios. The results of this study can be useful to AM practitioners in decision-making on the selection of the most sustainable manufacturing approach and choosing process parameters that ensure an environment and cost-efficient manufacturing of their product.

## 3. Manufacturing of marine propellers

A marine propeller is used to drive a ship or boat in water. The propeller is connected to the main engine of the ship through a shaft. As the engine starts, the propeller rotates and applies a linear thrust on water which in turn exerts a reactive force on the ship and the ship moves ahead. This section reviews the manufacturing of marine propellers by presenting studies that have demonstrated the fabrication of marine propellers using conventional subtractive manufacturing, SLM, and WAAM technologies.

### 3.1. Manufacturing of marine propellers by pure CNC milling

Maine propeller blades tend to have complex geometries and must possess high precision requirements for ensuring a better quality of the propulsion system. Hence, propellers are traditionally manufactured using computerized numerical control (CNC) technology, mostly by 5-axis CNC machine tools [35]. The benefits of using 5-axis CNC machines include shorter processing times, set-up times, and better surface quality due to their inherent ability to position the tool and workpiece at multiple points and angles, improving their accessibility and productivity [36]. During the CNC machining of a marine propeller, firstly, a workpiece which is generally in the form of a cylindrical bar is mounted on the work-holding device. An appropriate cutting tool and cutting parameters must be selected, and the toolpath motion is generated and simulated in order to verify if the toolpath is free of collisions. Then the actual material removal is carried out by performing a rough machining followed by finish machining to achieve the required dimensional and surface tolerances. These steps involved in 5 axis CNC machining are depicted in Fig. 1.

### 3.2. Manufacturing of marine propellers by selective laser melting

SLM is a powder bed fusion (PBF) type AM process that uses a high-power laser beam as the source of energy to melt and fuse metal powders layer-by-layer to fabricate a given geometry. This process is carried out in a chamber filled with inert gas such as argon or nitrogen, to prevent or decrease the interaction between the molten metal and oxygen. SLM can produce highly complex parts, produces strong and tough metal parts, and can be used for a wide range of metals but requires very costly machine tools and materials [38]. The manufacture of marine propellers by SLM has been demonstrated in some studies in the past few years. Scudino et al. [39] fabricated a marine propeller from Cu—10Sn bronze powder using SLM. The SLM made specimen showed superior ultimate tensile strength in the range of 220–420 MPa and ductility of 17 %, compared to as-cast specimens that had an ultimate tensile strength varying between 120 and 180 MPa and ductility of 7 % (see Fig. 2). However, the surface roughness of the SLM fabricated propeller is higher and hence, it would require further post-processing operations to achieve the desired surface finish. Staiano et al. [40] demonstrated that AlSi10Mg could be used for the fabrication of a propeller using Directed Metal Laser Sintering (DMLS) process.

### 3.3. Manufacturing of marine propellers by wire arc additive manufacturing

In WAAM, a metal wire is used as a feedstock material, and an electric arc is used as an energy source to melt it. The molten metal is then deposited layer-by-layer to fabricate a part (a marine propeller in this case) as illustrated in Fig. 3. A shielding gas, generally an inert gas like argon, is used while printing to protect the molten metal pool from detrimental atmospheric interactions. The major advantages of this process include higher deposition rates than PBF processes, the ability to fabricate medium-to-large components [11], and lower machine and material costs [13]. However, it also has disadvantages such as the presence of higher residual stresses, and poor accuracy, and hence requires post-processing operations [14]. Although this technology has not been fully industrialized, various pilot-scale projects of using WAAM to fabricate marine propellers have been reported by different research institutions and industries [12]. A nickel-aluminium-bronze (NAB) alloy marine propeller of 1355 mm in diameter weighing 400 kg was fabricated by RAMLAB in collaboration with Damen Group, Burea Veritas, Promarin and Autodesk [41]. In another initiative, two South Korean companies SY Metal and DNV manufactured a NAB marine propeller weighing 520 kg with a diameter of 2 m [42]. Moreover, the WAAM

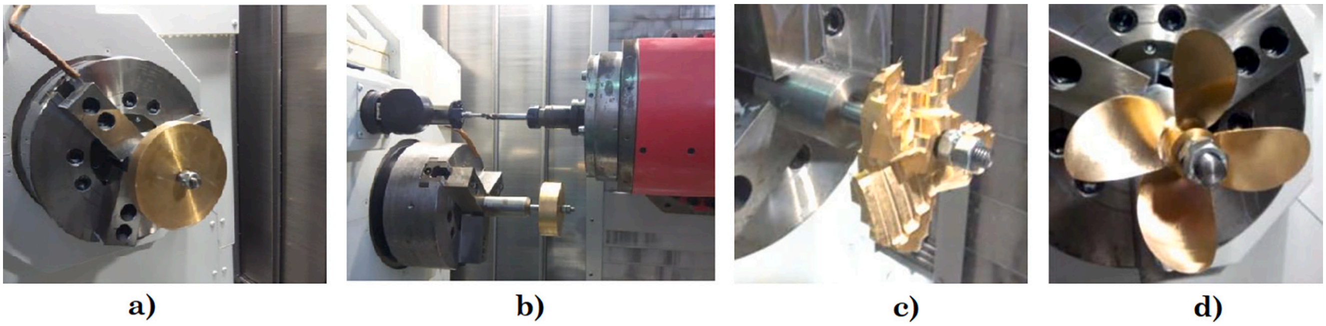


**Fig. 1.** Steps involved in 5-axis CNC machining of a marine propeller a) workpiece installation b) cutting tool setting c) roughing d) finishing as demonstrated by Rahman et al. [37].

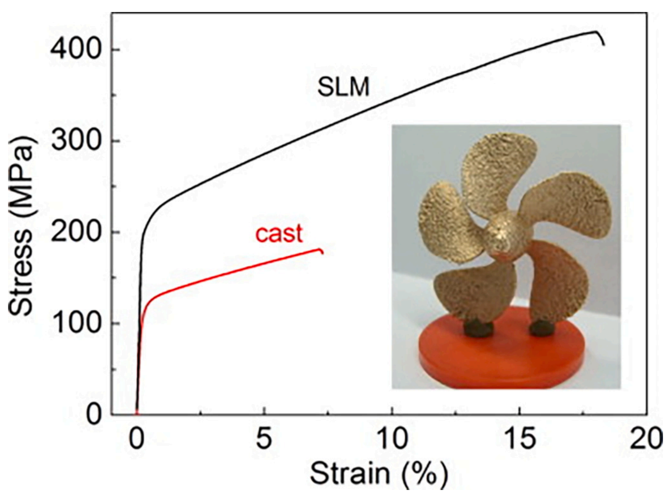


**Fig. 2.** SLM fabricated Cu—10Sn bronze propeller and its stress-strain curve by Scudino et al. [39].
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made propeller exceeded the mechanical and chemical requirements of the cast propeller specified by the Ship Rules. Ya and Hamilton [43] demonstrated the WAAM fabrication of 2 four-blade marine propellers of diameters 0.5 m and 1 m with blade thicknesses of 10 mm and 15 mm respectively and 1 three-blade propeller of 0.36 m diameter and variable blade thickness. The different propellers manufactured by WAAM in the above studies are illustrated in Fig. 3.

## 4. Methodology

A common tool for calculating the ecological impacts of a product across its lifespan is life cycle assessment (LCA). The ISO 14044:2006 standard outlines the LCA framework [45]. A product's partial or complete life cycle costs are assessed using the life cycle costing (LCC) methodology. Decisions to reduce the product cost without violating the expectations of any stakeholder may be made via an LCC evaluation [46]. In this study, a WAAM-built product is simultaneously subjected to an economic and environmental evaluation using LCC and LCA, respectively. The methodology to carry out a combined LCA and LCC assessment and the outcomes achieved from its implementation are illustrated in Fig. 4.

The stages involved in carrying out this combined LCA and LCC evaluation are as follows:

- The first phase clearly defines the study's goal and scope. The life cycle stage(s) that must be taken into account in the evaluation is referred to as the scope in this case.
- The gathering of environmental inventory data, including data on raw materials, energy, shielding gases, material waste emissions, and economic inventories, which includes expenses related to these resources used in the manufacture of products, is the second phase.
- Based on the inventory obtained in the second stage, the ecological impact and overall cost are calculated in the third stage.
- In the last phase, the results are thoroughly examined, and the main causes of environmental impacts and costs are identified. Moreover, solutions for enhancing both environmental and economic sustainability are also suggested at this stage. This methodology is also transferable to other subtractive as well as additive manufacturing processes.

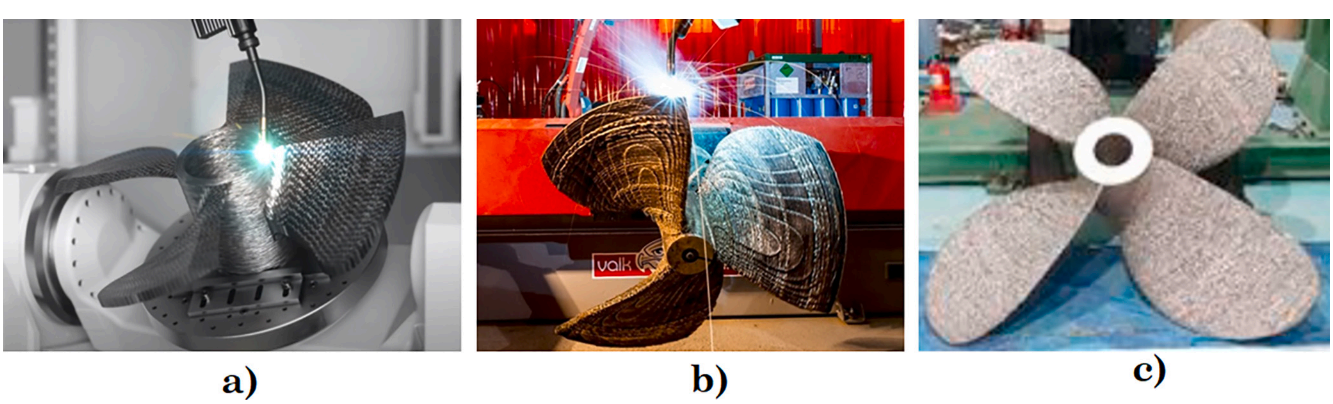


**Fig. 3.** a) WAAM fabricated propeller by GEFERTEC Gmbh [44] b) WAAM printed NAB propeller by RAMLAB/Damen Shipyards [41] c) NAB WAAM propeller by SY Metal and DNV as shown by Govindaraj et al. [42].
(Image used with permission from Elsevier.)

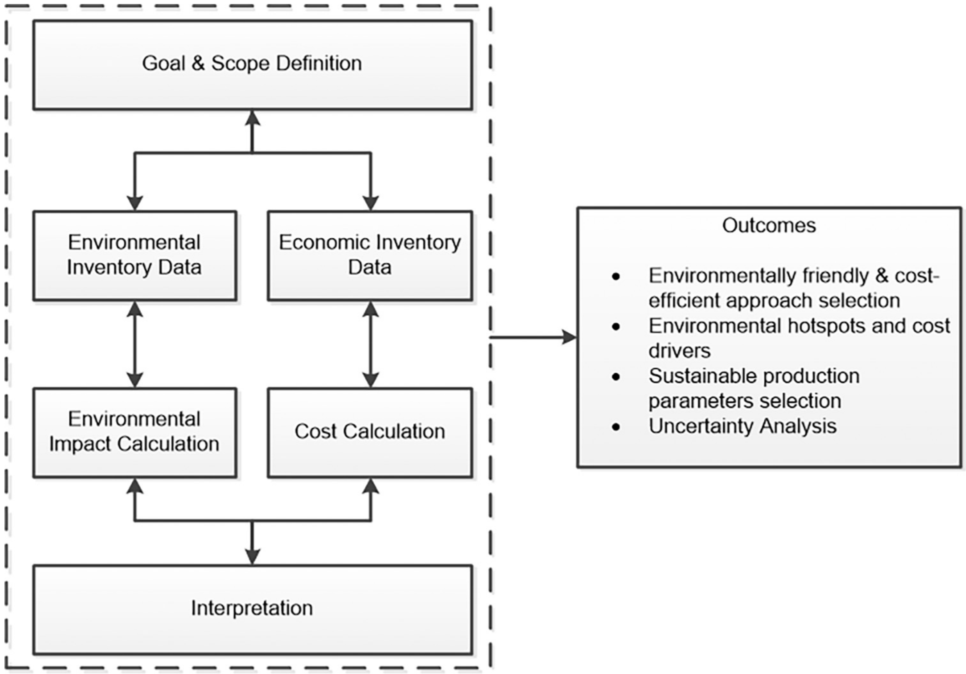


**Fig. 4.** Methodology used in this study.

## 5. Case study

This section aims to examine the environmental impacts and production costs associated with manufacturing a propeller by two AM processes, namely WAAM, SLM, and one conventional manufacturing (CM) process of CNC milling. A marine propeller is used to drive a ship or boat in water. The propeller is connected to the main engine of the ship through a shaft. As the engine starts, the propeller rotates and applies a liner thrust on water which in turn exerts a reactive force on the ship and the ship moves ahead. This case study examines a four-blade propeller (refer to Fig. 5) made of ER70 steel. The propeller is 100 mm in diameter and 30 mm in height. The outward diameter of the central rotating hub is 30 mm, while the internal diameter is 15 mm. This propeller has a volume of 26 $cm^3$ and a surface area of 159 square centimetres with a maximum blade thickness of 3 mm. Taking into account steel's density of 7.8 g per cubic centimetre, the weight of this propeller is calculated as 204 g.

### 5.1. Goal and scope definition

The main goal of this study is to evaluate and compare the environmental footprint and cost incurred while manufacturing a given product using WAAM, SLM, and pure CNC machining approaches. The purpose of this study is to identify which process is most sustainable, both environmentally and economically. This LCA is prospective, i.e., it evaluates an emerging WAAM technology that is still in its nascent stages of development compared to SLM and CNC milling, but it models WAAM technology at a later, advanced stage [47]. The results of this

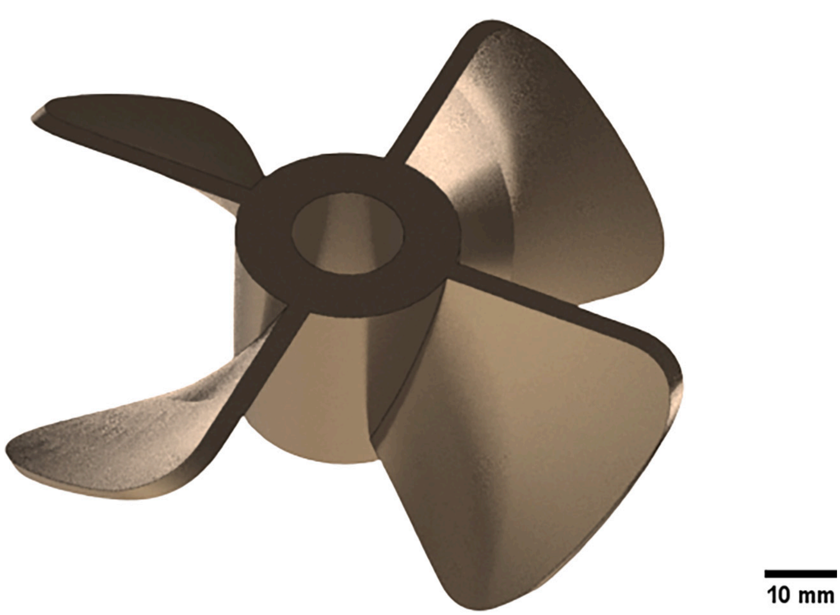


**Fig. 5.** Propeller analyzed in this study.

study can help AM practitioners in the selection of the most sustainable manufacturing alternative for manufacturing similar products and take full advantage of its sustainability potential to ensure resource and cost-efficient production. The system boundaries and scope of this investigation are illustrated in Fig. 6.

This study is a cradle-to-gate study i.e., it starts from raw material extraction (cradle) and ends at the workshop (gate) where the product is produced before its shipment to the customer. The inspection of the propeller is excluded as the final part produced by all 3 manufacturing is the same and hence, the inspection steps in all 3 approaches will be identical. Studies have shown that parts produced by WAAM [48] and SLM [49] can demonstrate excellent mechanical properties, comparable to the bulk material properties. Therefore, it is assumed that the propeller produced by all 3 approaches will have the same performance level and lifespan under identical conditions of operation. Therefore, use and disposal stages can be excluded. The transportation of raw materials is also not included in the scope of this study as it is realized in a previous study by the authors [32] that the contribution of raw material transportation to the overall impacts of WAAM, SLM, and CNC machining is insignificant (<1 %). A functional unit is to reference using which the input and output inventory flows are mapped [50]. In this study, one unit of the propeller manufactured separately by WAAM, SLM, and CNC milling approaches is considered the functional unit. Additionally, it is assumed that the steel billet used for manufacturing feedstock materials

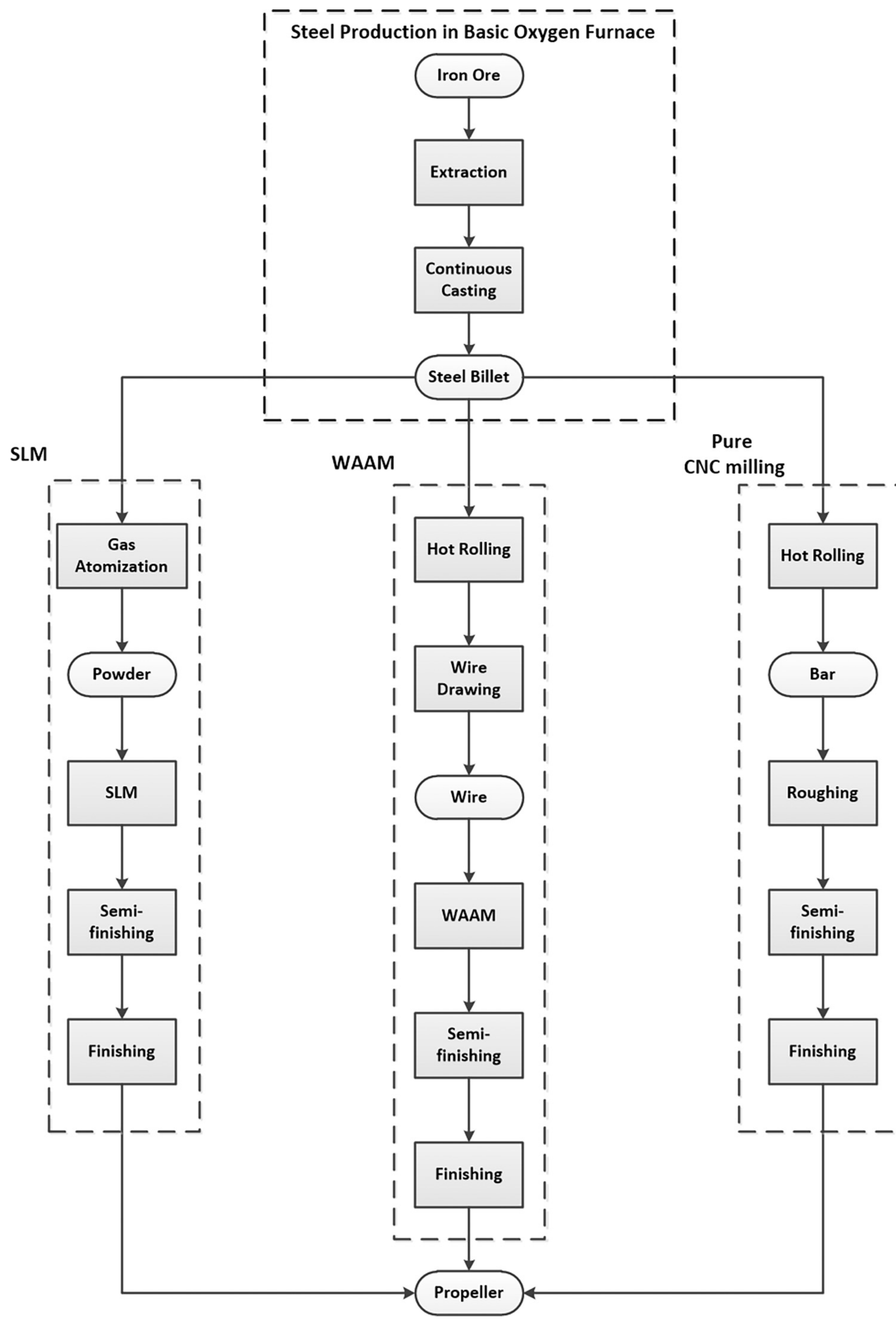


**Fig. 6.** Cradle-to-gate system boundaries for WAAM, SLM, and CNC milling approaches analyzed in this study.

i.e., powder for SLM, wire for WAAM, and bar for CNC milling are produced from the same type of steel billet manufactured using blast oxygen surface (BOF).

### 5.2. Environmental inventory analysis

The life cycle inventory data (LCI) for each manufacturing is presented in this section. The data collection process based on experimental data, simulations, existing LCI databases, and other relevant literature, is discussed in the following subsections.

#### 5.2.1. Pure CNC milling approach

The pure subtractive approach for manufacturing the propeller starts with the production of a cylindrical bar from the steel billet using a hot rolling process. The life cycle inventory data for the still billet and hot rolling process is taken from the Ecoinvent 3 database [51]. Ecoinvent 3 database considers a material efficiency of 95 % for the hot rolling process. In this case, the raw material considered is a cylindrical bar with a diameter of 102 mm and a height of 32 mm. The cylindrical bar is then milled to the final propeller geometry by following strategy: roughing, semi-finishing, and finishing, as illustrated in Fig. 7, using a 10 mm carbide endmill with 4 cutting teeth. As recommended by the tool manufacturer [52], we consider the following cutting parameters: roughing ($V_c = 93$ m/min; $f_z = 0.09$ mm, ap = 2.5 mm); semi-finishing ($V_c = 71$ m/min; $f_z = 0.09$ mm, $a_p = 0.5$ mm); and finishing ($V_c = 71$ m/min; $f_z = 0.09$ mm, $a_p = 0.1$ mm).

Based on the toolpath simulation in SolidWorks CAM, the total cutting time is 6 h 5 min. In addition to this time, 30 min for setting up and preparation of the CNC machine are considered. The electricity consumed during the process is calculated based on the current and voltage monitored using sensors in Digilent Waveforms software. A total of 4.65 kWh of electricity is consumed in this approach. The cutting fluid consumed during the machining process could not be monitored and hence, the value for the cutting fluid consumed is taken from the Ecoinvent 3 database. The environmental inventory of the pure CNC machining approach is enlisted in Table 1.

**Table 1**
Environmental inventory for pure CNC milling approach.

| Inventory | Amount | Reference |
|---|---|---|
| Raw material production | | |
| Steel billet | 2.13 kg | Ecoinvent 3 database |
| Hot Rolling | 2.13 kg | Ecoinvent 3 database |
| CNC milling | | |
| Steel bar | 2.02 kg | Calculated |
| Material waste | 1.814 kg | |
| Electricity | 4.65 kWh | Calculated |
| Cutting fluid | 30.25 kg | Ecoinvent 3 database |

#### 5.2.2. Wire arc additive manufacturing approach

The WAAM approach begins with the production of the feedstock wire used as raw material. The feedstock wire is manufactured by hot rolling followed by wire drawing of a steel billet. As mentioned previously, a steel billet manufactured using a blast oxygen furnace is used as the primary raw material for all three approaches. For modeling the steel billet, inventory flow "steel production, converter, low-alloyed RER" from the Ecoinvent 3 database is used. The life cycle inventory data for hot rolling and wiredrawing stages is also taken from the same database. In accordance with this database, material wastage of 5 % and 4 % are considered for the hot rolling and wire drawing stages, respectively. The feedstock wire of 1 mm in diameter is used. As-built WAAM products often have wavy surfaces and poor dimensional accuracy, making it necessary to use post-processing processes such as finish machining necessary to achieve the required dimensions. As a result, a WAAM-built product must incorporate a sufficient material allowance across its surface area to accommodate material removed during finish machining. In a previous study by the authors, involving the fabrication of a 3 mm thick flat ER70 steel wall, the thickness of the as-built WAAM wall was kept at 6.7 mm, corresponding to a machining allowance of the depth of 1.85 mm across the wall's surface area. Similarly, Campatelli et al. [29] used a weld bead thickness of 6.8 mm to ensure sufficient material allowance for machining a structural steel airfoil profile having a maximum thickness of 3 mm which results in about 1.9 mm deep machining allowance on each side of the airfoil. As the propeller blades are also 3 mm in thickness, a finish machining allowance corresponding to a uniform depth of 2 mm across the surface area of the propeller is considered. This machining allowance corresponds to 248 g (or 31.8 $cm^3$) in addition to the final part weight of 204 g (or 26.15 $cm^3$). The WAAM depositions are driven by 3 m/min wire feed speed, 360 mm/min axes travel speed and 1.3 mm layer height. Based on these parameters, it takes 15 min to print the given part according to the toolpath movement simulation in a commercial slicing software Prusa 3D. Additionally, after printing each layer, the part is allowed to be cooled for 120 s. A shielding gas of composition 82 % Argon and 18 % $CO_2$ at a flow rate of 16 l/min is employed to protect the molten pool from atmospheric interactions. The process parameters used for WAAM are given in Table 2. The post-processing of the as-built WAAM part is carried out in two stages, i.e., semi-finishing and finishing using CNC milling. A carbide endmill of 10 mm in diameter with 4 cutting teeth is considered here. The cutting parameters are used for each stage based on the recommendations made by the cutting tool manufacturer [52] as described in Table 2. The cutting tool motion is simulated in SolidWorks Cam software. The total cutting time obtained is 3 h 43 min. Additionally, a setup time of 30 min is considered. The detailed environmental inventories in each step involved in the WAAM approach are listed in Table 3.

#### 5.2.3. Selective laser manufacturing approach

For the SLM approach, metal powder is the raw material. The metal powder is produced using a process called gas atomization. In the gas atomization process, the metal billets are melted and subjected to a high-speed stream of argon gas which disintegrates it into fine particles. These particles are then cooled to form a metal powder. The life cycle

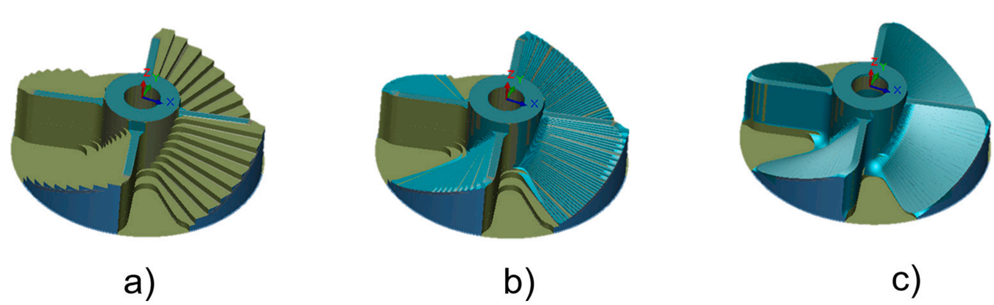


**Fig. 7.** CNC milling strategy: a) Roughing, followed by b) Semi-finishing and c) Finishing of the part.

**Table 2**
Parameters used for WAAM approach.

| Process parameters | Values |
|---|---|
| WAAM | |
| Wire feed speed | 3 m/min |
| Travel speed | 360 mm/min |
| Layer height | 1.3 mm |
| Interlayer cooling time | 120 s |
| Preparation time | 30 min |
| Printing time | 15 min |
| Cooling time | 46 min |
| Total WAAM time | 91 min |
| Post-processing | |
| Semi-finishing | |
| Cutting velocity ($V_c$) | 71 m/min |
| Feed per tooth ($f_z$) | 0.09 mm |
| Depth of cut ($a_p$) | 0.5 mm |
| Finishing | |
| Cutting velocity ($V_c$) | 71 m/min |
| Feed per tooth ($f_z$) | 0.09 mm |
| Depth of cut ($a_p$) | 0.1 mm |
| Cutting time | 3 h 43 min |
| Setup time | 30 min |
| Total post-processing time | 4 h 13 min |
| Total manufacturing time | 5 h 44 min |

**Table 3**
Environmental inventory for WAAM approach.

| Inventory | Amount | Reference |
|---|---|---|
| Raw material production | | |
| Steel billet | 0.497 kg | Ecoinvent 3 database |
| Hot Rolling | 0.497 kg | Ecoinvent 3 database |
| Wire drawing | 0.472 kg | Ecoinvent 3 database |
| WAAM | | |
| Steel wire | 0.453 kg | Calculated |
| Electricity | 0.507 kWh | Measured |
| Shielding gas | 0.24 $m^3$ | Calculated |
| Post-processing | | |
| Milling chips | 0.249 kg | Calculated based on 2 mm machining allowance |
| Electricity | 2.91 kWh | Measured |
| Cutting fluid | 4.13 kg | Ecoinvent 3 database |

inventory data was obtained from a previous study by Peng et al. [21] involving the gas atomization of stainless steel. This study collected the life cycle inventory data for gas atomization from the powder's supplier. Therefore, this study is used as a source of gas atomization inventory data. According to this study, the gas atomization process has a material of 85 % and an energy requirement of 2 kWh/kg for powder production. This process also consumes water at a rate of 280 l/kg and argon gas at a rate of 3.5 $Nm^3$/kg of the powder produced. The process parameters for SLM based on studies involving the manufacturing of stainless steel flat washers [22] and carburizing steel gear [34] are considered as follows: laser scan speed of 1100 mm/s, hatch distance corresponding to 100 μm and layer thickness equal to 50 μm. These parameters correspond to a build rate of 19.8 $cm^3$/h. The recoating time between two consecutive layers is maintained at 7 s. As SLM has a better surface finish of <50 μm generally [53], a uniform machining allowance of 1 mm is left across the product's surface area, as considered by [54]. Additionally, the powder required for building support structures while fabricating the product is also considered. Additionally, 10 % of the part weight is considered as the material allowance for building the support structures while printing, based on the printing simulation in Prusa 3D slicer. The SLM process is carried out in five different phases or production modes, that are as follows: (i) Preparation mode where the machine and material are made available, (ii) Preheating mode where the process chamber is preheated to reduce thermal gradient and an inert gas is flooded to create an inert atmosphere to avoid oxidation during the SLM process, (iii) Exposure mode where the laser selectively scans and melts the powder, (iv) Recoating mode where a new layer of powder is recoated, and (v) Cooling mode where the printed part is allowed to cool. Each mode has a different electricity requirement and some modes like preheating require consumables like inert gas in addition to electricity. Only two studies, one by Kellens et al. [55] and the other by Gebbe et al. [56] have recorded detailed production mode-wise energy, compressed air, and argon consumption inventories for SLM of steel. As the study by Gebbe et al. [56] is more recent than Kellens et al. [55], compressed air, electricity, and argon gas required for the initial flooding of the machine chamber are calculated based on the resource consumption measurement study performed be Gebbe et al. [56]. These calculations are displayed for each step involved in SLM in Table 4. For post-processing of the as-built SLM part, strategies similar to the WAAM approach are considered, i.e. semi-finishing ($V_c = 71$ m/min; $f_z = 0.09$ mm, $a_p = 0.5$ mm) followed by finishing ($V_c = 71$ m/min; $f_z = 0.09$ mm, $a_p = 0.1$ mm) using a carbide Ø10 mm endmill. The post-processing takes 3 h 38 min and consumes 2.84 kWh of electricity. The detailed list of inventories consumed in the SLM approach is compiled in Table 5.

### 5.3. Economic inventory analysis

A cost model that has a scope limited to cradle-to-gate has been developed by the authors to calculate the life cycle costs associated with WAAM, SLM, and pure CNC machining methods [32]. As per this cradle-to-gate cost model, the following costs are taken into account:

(i) Machine Cost ($C_{machine}$): This cost includes costs associated with the buying, maintenance, and tooling of machine tools. It is calculated as follows:

$$C_{machine} = \left(\frac{C_{mct} + C_{mt} + C_{tooling}}{t_{available}}\right) \times t_{machine} \quad (1.1)$$

where:

- $C_{mct}$ (€): Purchasing cost of a machine tool.
- $C_{mt}$ (€): Maintenance cost of a machine tool.
- $C_{tooling}$ (€): Cost of tooling such as jigs, fixtures and cutting tools.
- $t_{available}$ (h): Total available time of a machine tool.
- $t_{machine}$ (h): time for which a machine is used including its set-up, processing time and clean-up.

(ii) Material Cost ($C_{material}$): It is the cost of the raw materials i.e., metal wire, powder, or bar consumed in a corresponding manufacturing approach and is computed as follows:

$$C_{material} = m_{material} \times MC_{1kg} \quad (1.2)$$

where:

- $m_{material}$ (kg): the amount of the total raw material consumed including the final part and waste material.
- $MC_{1kg}$ (€/kg): Cost of 1 kg of raw material.

(iii) Consumables Cost ($C_{consumables}$): This encompasses the cost of different consumables required in each process such as electricity, shielding gas (in the case of WAAM and SLM), or cutting fluid (in case of CNC machining). It can be computed as follows:

$$C_{consumables} = e_{part} \times EC_{1kWh} + g_{part} \times GC_{1m^3} \quad (1.3)$$

where,

- $e_{part}$ (kWh): The amount of electricity consumed in a part fabrication.

**Table 4**
Energy, compressed air and argon gas consumption for SLM based on Gebbe et al. [56].

| SLM production mode | Time (h) | Electricity | | Compressed air | | Argon | |
|---|---|---|---|---|---|---|---|
| | | Power (kW) | Energy (kWh) | Flow rate (l/min) | Total ($m^3$) | flow rate (l/min) | Total ($m^3$) |
| Preparation | 0.5 | 0.363 | 0.18 | 0 | 0.00 | 0 | 0 |
| Preheating | 0.5 | 2.523 | 1.26 | 0 | 0.00 | 40 | 1.2 |
| exposure | 2.27 | 2.625 | 5.96 | 16.7 | 2.27 | 0 | 0 |
| recoating | 1.28 | 2.625 | 3.36 | 16.7 | 1.28 | 0 | 0 |
| Cooling | 2 | 0.363 | 0.73 | 0 | 0.00 | 0 | 0 |
| Total | 6.55 | | 11.49 | | 3.56 | | 1.2 |

**Table 5**
Environmental inventory for SLM approach.

| Inventory | Amount | Reference |
|---|---|---|
| Raw material production | | |
| Steel billet | 0.414 kg | Ecoinvent 3 database |
| Gas atomization | | |
| Electricity | 0.828 kWh | Peng et al. [21] |
| Argon | 2.58 kg | Peng et al. [21] |
| Water | 0.116 kg | Peng et al. [21] |
| SLM | | |
| Steel powder | 0.352 kg | Calculated based on CAD model and 10 % allowance for supporting structures |
| Electricity | 11.49 kWh | Gebbe et al. [56] |
| Compressed air | 3.56 $m^3$ | Gebbe et al. [56] |
| Argon | 1.2 $m^3$ | Gebbe et al. [56] |
| Post-processing | | |
| Material waste | 0.116 kg | Calculated based on 1 mm uniform machining allowance |
| Electricity | 2.84 kWh | Calculated based on measured data |
| Cutting fluid | 1.94 kg | Ecoinvent 3 database |

- $g_{part}$ ($m^3$): The volume of inert/shielding gas consumed in a part fabrication.
- $EC_{1kWh}$ (€/kWh): Cost of 1kWh of electricity.
- $GC^3_{1m}$ (€/m3): Cost of 1 $m^3$ of inert/shielding gas.

(iv) Post-processing Cost ($C_{post\text{-}processing}$): It includes the costs associated with the post-processing operations involved in WAAM and SLM, in particular. Machines, consumables, and labour related to post-processing operations are included in this cost. It is calculated as follows:

$$C_{post-processing} = PPC_{1h} \times t_{post-processing} \tag{1.4}$$

where,

- $PPC_{1h}$ (€/h): The post-processing cost per hour
- $t_{post\text{-}processing}$ (h): Total post-processing time

(v) Labour Cost ($C_{labour}$): It involves the cost of the operator in performing various activities in each manufacturing approach such as preparation, set up, processing, post-processing, and clean up. It is computed by using the following equation:

$$C_{labour} = LC_{1h} \times t_{labour} \tag{1.5}$$

where,

- $LC_{1h}$ (€/h): Hourly cost of the operator.
- $t_{labour}$ (h): The total time required for all the activities associated with a manufacturing approach that requires the involvement of an operator.

For all 3 approaches, the machines are assumed to be used for 3 shifts of 8 h each, 250 working days each year, and a 7-year depreciation period. Machine availability is considered to be 80 % of the total time. Based on our vendors' quotations, WAAM, SLM, and CNC machine tools cost 300,000 euros, 500,000 euros, and 150,000 euros, respectively. The costs of maintenance and tooling are also considered each year, at 3 % and 2 % of the machine tool cost, respectively [57]. As a result, the machine costs for WAAM, SLM, and CNC milling machines are 12 €/h, 20 €/h, and 6 €/h, respectively. Based on supplier quotes, the steel wire used in WAAM costs 16 euros per kilogram, the steel bar used in CNC milling costs 5 euros per kilogram, and the steel powder costs 33 euros per kilogram. According to Eurostat electricity prices for Portugal [58], the cost of electricity is 0.13 €/kWh. According to its supplier's quotation, shielding gas costs 2.3 euros per meter. The hourly labour cost utilized in this study is 15 €/hr [59]. The approach-wise economic inventories are enlisted in depth in Table 6.

### 5.4. Environmental assessment

ReCiPe 2016 (Hierarchist) is used to conduct the environmental impact assessment of pure CNC milling, WAAM, and SLM approaches. A midpoint assessment evaluating the environmental impact expressed in 18 different environmental impact categories such as global warming, ozone depletion, particulate matter formation, acidification, and eutrophication, among others is carried out using ReCiPe 2016 Midpoint (Hierarchist) method. The results of the ReCiPe midpoint assessment are displayed impact category-wise in Table 7.

The results of these 18 environmental impact categories are translated into a single score impact (expressed in eco points) by using a weighing process in ReCiPe 2016 Endpoint (Hierarchist) method. The results of the ReCiPe endpoint are illustrated in Fig. 8.

Based on Fig. 8, it can be seen that WAAM is the most sustainable approach causing an environmental impact of 197 mPts, which is about 2.5 times lower than the pure machining approach (496 mPts) and nearly 3.4 times lower than the SLM approach (663 mPts). An

**Table 6**
Economic Inventory data used in this study.

| Cost | Manufacturing approach | | | Reference |
|---|---|---|---|---|
| | CNC milling | WAAM | SLM | |
| Machine tool cost (€) | 150,000 | 300,000 | 500,000 | Quotation |
| Maintenance cost (€) | 31,500 | 63,000 | 105,000 | Calculated |
| Tooling cost (€) | 21,000 | 42,000 | 70,000 | Calculated |
| Machine cost (€/h) | 6 | 12 | 20 | Calculated |
| Material cost (€/kg) | 5 | 16 | 33 | Quotation |
| Electricity cost (€/kWh) | 0.13 | 0.13 | 0.13 | [58] |
| Inert gas/shielding cost (€/$m^3$) | 2.3 | 2.3 | 2.3 | Quotation |
| Post-processing cost (€/h) | | 21 | 21 | Calculated |
| Labour cost (€/h) | 15 | 15 | 15 | [59] |

**Table 7**
ReCiPe Midpoint(H) assessment results.

| Impact category | Unit | Pure CNC milling | WAAM | SLM |
|---|---|---|---|---|
| Ionizing radiation | kBq Co-60 eq | 3.42E−01 | 4.24E−01 | 3.68E+00 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.94E+01 | 8.45E+00 | 1.53E+01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 4.74E−01 | 1.70E−01 | 5.63E−01 |
| Marine ecotoxicity | kg 1,4-DCB | 6.51E−01 | 2.31E−01 | 7.49E−01 |
| Human carcinogenic toxicity | kg 1,4-DCB | 3.92E+00 | 1.11E+00 | 1.54E+00 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 6.97E+00 | 3.23E+00 | 1.43E+01 |
| Stratospheric ozone depletion | kg CFC11 eq | 1.97E−06 | 1.19E−06 | 6.00E−06 |
| Global warming | kg CO2 eq | 7.16E+00 | 3.56E+00 | 1.51E+01 |
| Mineral resource scarcity | kg Cu eq | 2.97E−01 | 7.03E−02 | 7.05E−02 |
| Marine eutrophication | kg N eq | 2.26E−04 | 1.31E−04 | 6.60E−04 |
| Ozone formation, Human health | kg NOx eq | 1.79E−02 | 8.37E−03 | 3.39E−02 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1.88E−02 | 8.62E−03 | 3.43E−02 |
| Fossil resource scarcity | kg oil eq | 1.76E+00 | 9.12E−01 | 4.11E+00 |
| Freshwater eutrophication | kg P eq | 3.19E−03 | 1.75E−03 | 9.46E−03 |
| Fine particulate matter formation | kg PM2.5 eq | 1.23E−02 | 5.75E−03 | 2.41E−02 |
| Terrestrial acidification | kg SO2 eq | 2.54E−02 | 1.43E−02 | 6.60E−02 |
| Land use | m2a crop eq | 1.78E−01 | 8.29E−02 | 3.27E−01 |
| Water consumption | m3 | 5.44E−02 | 5.41E−02 | 3.68E−01 |

assessment of material consumption and cumulative energy demand (CED) for each approach is also presented in Fig. 9. The cumulative energy demand is the summation of energy consumed, both directly and indirectly, across a product's lifespan [60] and is calculated using the "Cumulative Energy Demand" methodology available in SimaPro software. SLM is observed to be the most material-efficient approach consuming the amount of raw material nearly 5.7 times lower than pure CNC milling and 22 % lower than the WAAM approach. However, SLM is the least energy-efficient approach requiring a cumulative energy of 307 MJ, which is nearly thrice the demand for the pure CNC milling approach and about 5 times the energy demand of the WAAM process. A similar trend was observed by Landi et al. [61] while comparing the environmental impact of CNC machining and a laser-based AM technology Laser Engineered Net Shaping (LENS) in manufacturing an AISI 4140 spur gear. The LENS approach showed a relatively better material efficiency of 31 % compared to the CNC milling approach which exhibited a material efficiency of 10 %. However, the LENS approach consumed about 7 times higher energy than the CNC milling approach. As a result, it was observed that both approaches performed better/worse than each other in some impact categories and overall, no approach was better than the other. Thus, the WAAM process is seen as the most balanced option in terms of material and cumulative energy requirements, when compared to pure subtractive and laser based additive approaches.

The contribution of each inventory input to these approaches is also studied. The results of this contribution analysis are depicted in Fig. 10. From Fig. 10, it is observed that the primary raw material for the pure CNC machining approach i.e., the steel billet is the major environmental hotspot, accounting for about 76 % (378 mPts) of the total environmental impact. The electricity consumed in the machining process accounts for another 19 % (95 mPts), while the hot rolling process to shape the steel billet into the stock bar is responsible for 4.5 % (23 mPts) of the overall environmental burden of this approach. For the WAAM approach, the steel billet is the major contributor to its total environmental burden, accounting for about 44 % (87 mPts). The electricity consumption in post-processing machining operations causes nearly 30 % (60 mPts) of the total environmental impact, followed by the shielding gas causing 12 % (24 mPts) of the overall environmental impact. The other inventory inputs such as electricity consumed during WAAM deposition, wire drawing, and hot rolling have minor contributions of 5 % (10 mPts), 5 % (10 mPts), and 2.5 % (5 mPts) respectively. In contrast to WAAM and pure CNC machining approaches, energy consumed during the SLM process is the major contributor to the environmental impact of the SLM approach, causing nearly 36 % (237 mPts) of the total environmental burden. The gas atomization step is responsible for 23 % (154 mPts) and inert gas causes 19 % (126 mPts) of the environmental impact. The steel billet itself is responsible for 11 % of the impact, but it should be noted that the raw material production i.e., steel billet production and gas atomization together lead to 34 % of the total environmental burden. Other small contributors to the environmental impact of this approach are the electricity consumed in post-processing operations (9 %) and the compressed air (2 %) consumed during the SLM operation.

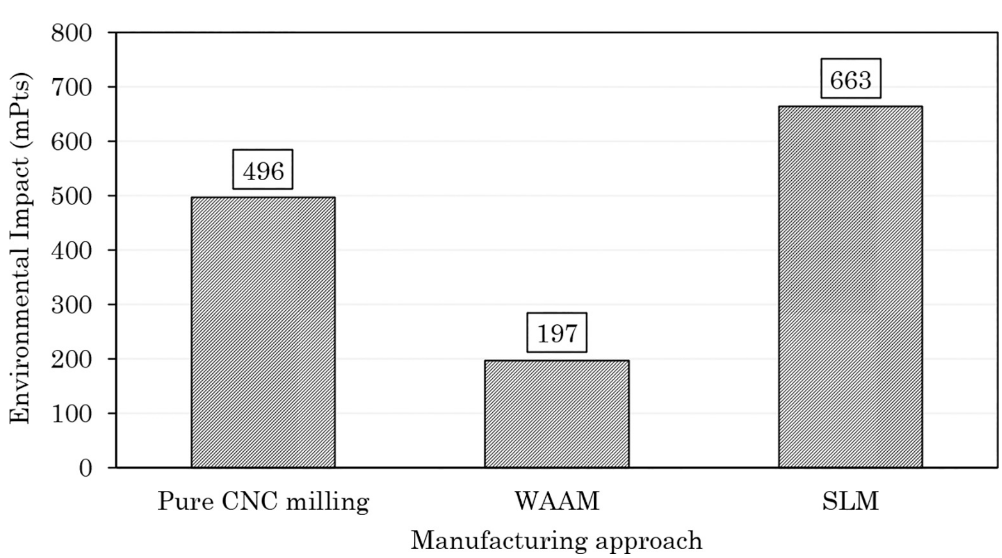


**Fig. 8.** Environmental Impacts of pure CNC milling, WAAM, and SLM expressed in millipoints (mPts).

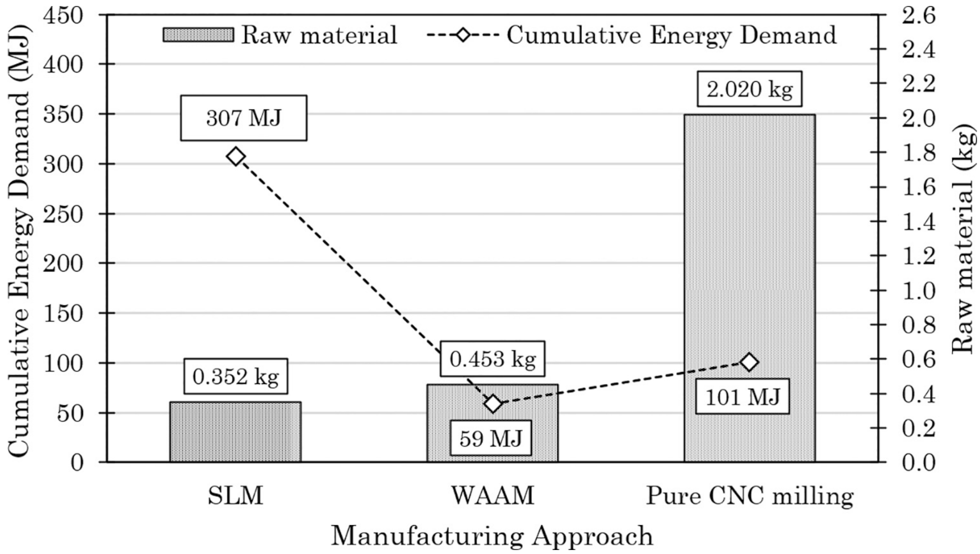


**Fig. 9.** Raw material and cumulative energy demand for WAAM, SLM, and pure CNC milling approaches.

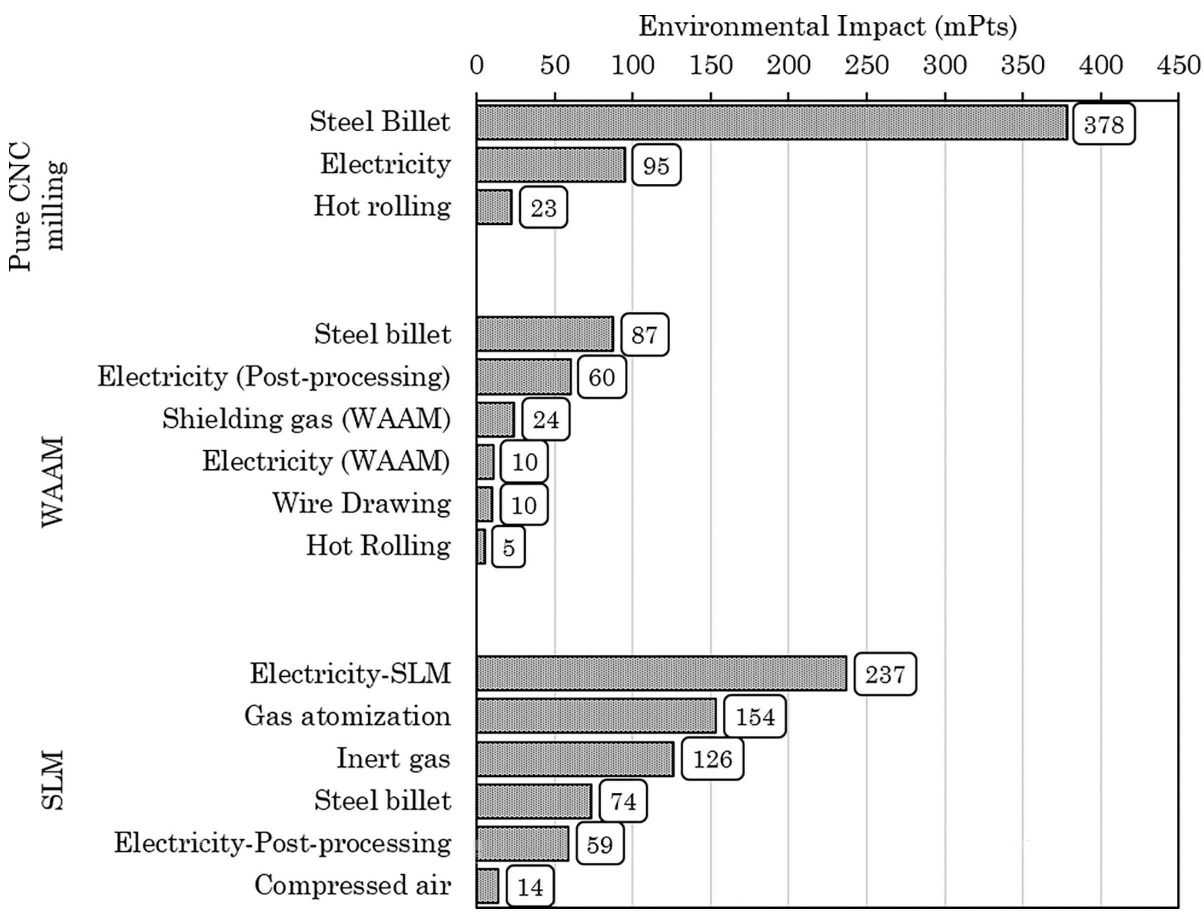


**Fig. 10.** The inventory-wise contribution to environmental impacts of pure subtractive, WAAM, and SLM approaches.

### 5.5. Economic assessment

Based on the economic inventory data collected and the cost model explained previously, the cost of producing the propeller considered is calculated for each manufacturing approach. The unit cost for the production of the propeller is as follows: 133 € for WAAM, 144 € for pure machining, and €338 for SLM approaches (refer to Fig. 11). Therefore, the WAAM approach is observed to be the most economical one among the 3 approaches studies. The major cost driver in the WAAM is the post-processing stage which accounts for nearly two-thirds of the unit production cost. Another 16 % of the unit cost originates from labour while the machine cost contributes 12 % of the unit cost. The material i.e., wire cost constitutes 5 % of the unit cost while the contribution of consumables is negligible (~1 %). In the pure CNC machining approach, labour

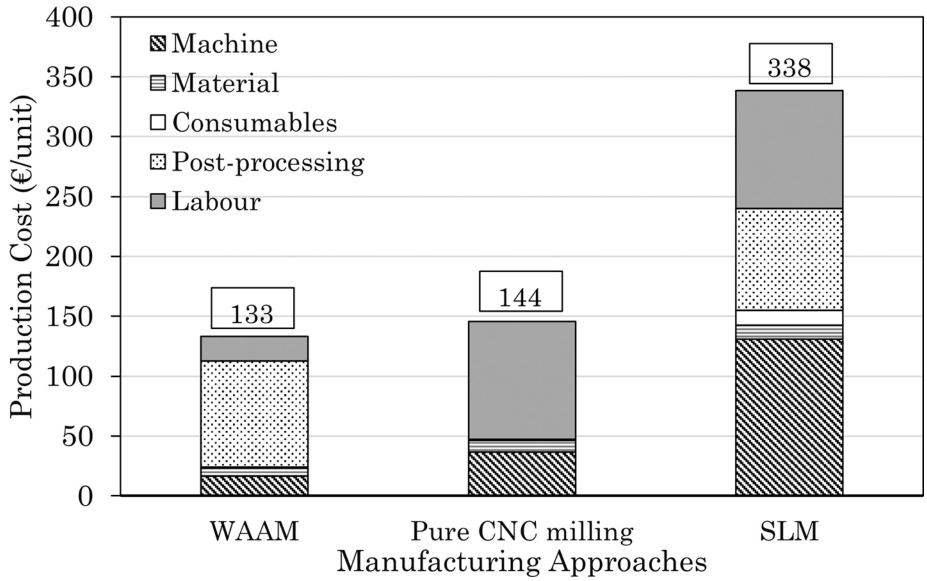


**Fig. 11.** Unit production cost for WAAM, pure CNC milling, and SLM approaches.

cost is the highest contributor representing 68 % of the total unit cost followed by machine cost (25 %) and material cost (7 %). In the SLM approach, machine cost is the key cost driver that accounts for 39 % of the total production cost. Other significant contributors to the production cost here are machine cost (29 %) and post-processing cost (25 %). The consumables and raw materials have relatively lower contributions of 4 % and 3 % respectively.

## 6. Discussions, uncertainty analysis, and limitations

This section discusses the impact of some key variables like the type of raw material (bar, wire, and powder), electricity mix, post-processing material allowance, and cutting velocity during finish machining. Additionally, an uncertainty analysis is done to take into consideration the effect of uncertainties in input data sources in the following subsections.

### 6.1. *Effect of raw material type*

In this study, AM processes are seen to be more material-efficient than the pure CNC milling approach. SLM displayed a material efficiency of 58 %, consuming raw material (powder) 1.3 times lower than WAAM and 5.8 times lower than the pure CNC milling approach. WAAM approach requires about 4.5 times lesser material (wire) than the pure CNC milling approach (cylindrical bar). However, according to the results of the environmental assessment, WAAM is the most environmentally friendly alternative, causing an environmental impact nearly 2.5 times lower than pure CNC milling and about 3.4 times lower than SLM. This can be attributed partially to the type of raw materials involved in each process. Based on the environmental inventory used in this study and assessment carried out using the ReCiPe Endpoint (H) method, the production of 1 kg of each steel bar, steel wire, and steel powder causes an environmental impact of 198 mPts, 229 mPts, and 645 mPts, respectively (see Fig. 12). The production of raw material for WAAM and SLM is observed to cause an environmental impact around

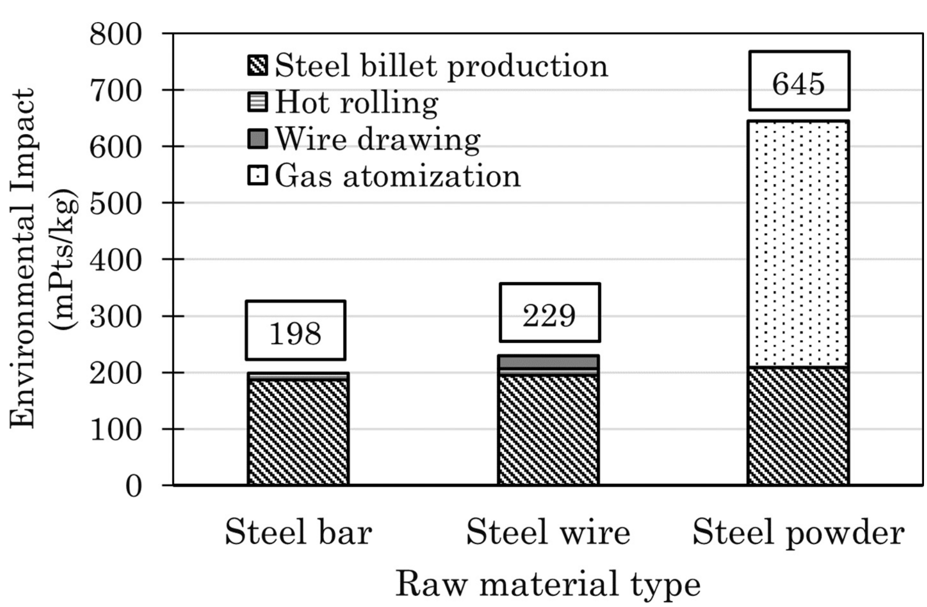


**Fig. 12.** Environmental impact for production of 1 kg steel bar, steel wire, and steel powder.

1.16 and 3.25 times, respectively higher than the steel bar due to additional processing steps like wire drawing and gas atomization. Similarly, the cost of steel powder (33 €/kg) used in SLM is about 6.6 times costlier than steel bar (5 €/kg) and around two times more expensive than the steel wire (16 €/kg) used in WAAM. Raw material production (steel billet production and its processing into feedstock material) accounts for 81 %, 52 %, and 34 % of the total environmental impact of CNC milling, WAAM, and SLM approaches, respectively. Therefore, from an environmental perspective, WAAM or SLM approaches can be adopted only in the cases where raw material savings achieved by their adoption outweigh the excessive environmental impact caused by the production of their feedstock materials (wires and powders). From an economical perspective, the raw material cost has a lower contribution (<7 %) in all three approaches. Hence, the adoption of a manufacturing approach is not heavily influenced by material cost, in this study.

### 6.2. Effect of the electricity mix

The electricity consumed during the processing and post-processing (in the case of WAAM and SLM) is seen to be a note-worthy contributor to the environmental impact of each approach considered in this study. The energy consumed during processing and post-processing accounts for 19 % of the total impact in the pure CNC milling approach, 36 % of the total impact in the WAAM approach, and 45 % of the total impact in the SLM approach. As this study is performed in Portugal, the electricity mix of Portugal is considered the baseline scenario in this study. To study the effect of electricity mix on the environmental impact, the following electricity mixes of the following countries with their share of electricity from fossil fuels (indicated in parenthesis) based on the statistical data provided by Our World in Data [62] are considered: India (78 %), China (66 %), Portugal (37 %), France (9 %), and Norway (0.5 %). The results of this assessment are indicated in Fig. 13. From Fig. 13, it is observed as the share of fossil fuels in electricity decreases, the environmental impact of each approach also decreases. As the content of fossil fuel in the electricity decreases to 0.5 % (Norwegian mix) from the current scenario (Portuguese mix), the environmental impact of CNC milling decreases by 18 %, WAAM decreases by 33 % while that of SLM decreases by 41 %. WAAM is seen to be the most environmentally friendly approach of all the electricity mixes considered. It is interesting to note that with the use of the Norwegian electricity mix, SLM is seen to be slightly more eco-friendly (389 mPts) than the pure CNC milling approach (408 mPts).

### 6.3. Effect of post-processing allowance

In this study, a uniform post-processing allowance of 2 mm across the product's surface area is considered to accommodate the surface waviness of the WAAM process that in turn is eliminated by machining operations. WAAM is observed to be environmentally cleaner due to its better material efficiency (48 %) compared to that of the pure subtractive approach (10 %). Insufficient post-processing material allowance can lead to a failure in achieving finished surfaces causing wastage of material, consumables, and labour. On the other hand, excessive post-processing material allowances lead to increased material consumption, lower material efficiency, and an increase in post-processing time which further drives up the production cost. Moreover, the material consumed is the major environmental. Therefore, the effect of varying post-processing material allowance on WAAM's material efficiency, environmental impact, and production cost must be studied. The post-processing material allowance in the range of 1 mm to 5 mm across the product's surface area is considered. Fig. 14 illustrates the variation in WAAM's material efficiency by varying the post-processing material allowance between 1 mm and 5 mm. As this allowance ranges from 1

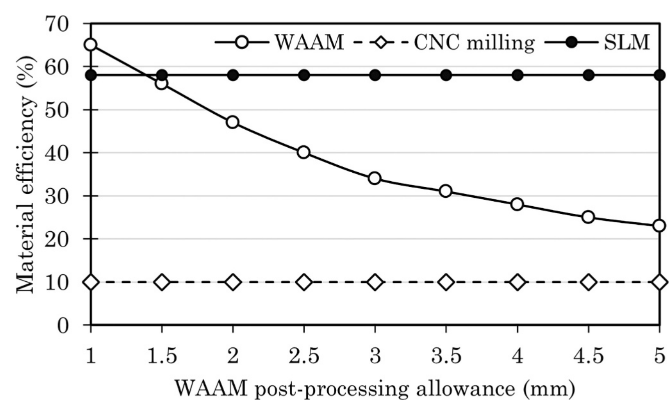


**Fig. 14.** Correlation between material efficiency and post-processing allowance for WAAM.

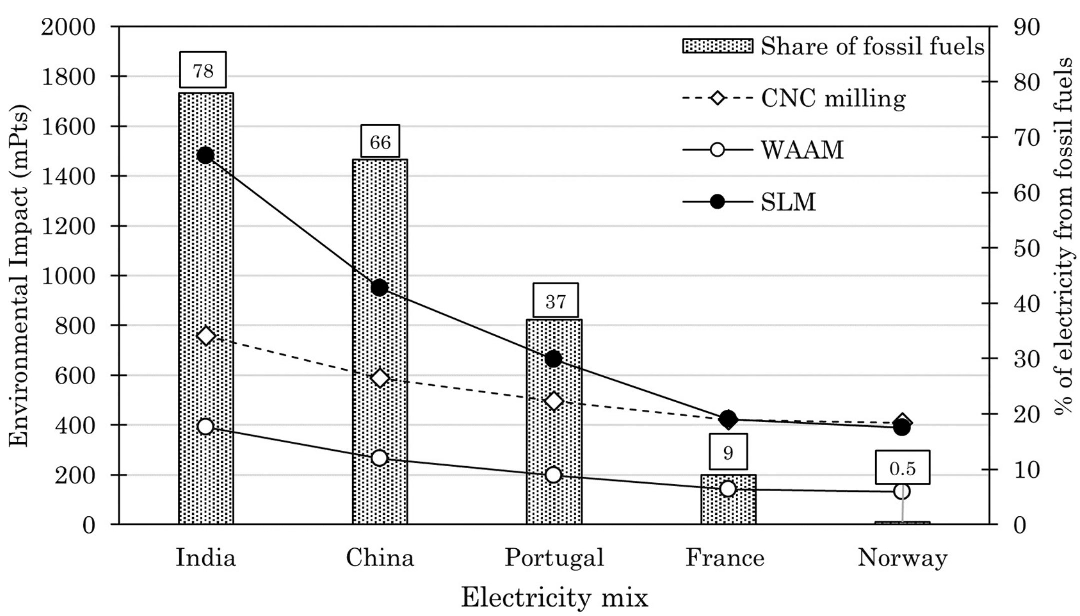


**Fig. 13.** Effect of electricity mix on the environmental impact.

mm to 5 mm, the material efficiency of WAAM differs from 65 % to 23 %. It is seen that at any allowance in this range, the material efficiency of WAAM is better than the material efficiency of pure CNC milling. The effects of varying this allowance on the environmental impact and unit production cost are displayed in Figs. 15 and 16, respectively. As the post-processing allowance is increased from 1 mm to 5 mm, the environmental impact for the WAAM approach rises from 153 mPts to 340 mPts, which is lower than that for pure CNC milling (496 mPts) and SLM (663 mPts) approaches. Similarly, the unit production cost for WAAM increases from 125 € to 150 € when this allowance increases from 1 mm to 5 mm. However, the WAAM approach is seen to be the most economical option only for the post-processing allowances under 4 mm, corresponding to material efficiencies higher than 28 % (refer to "Break-even point 1" in Fig. 16). For allowances, >4 mm, the pure CNC milling option is observed as the cheapest manufacturing approach for the product considered.

### 6.4. Effect of cutting velocity

Cutting velocity is an important parameter in the finish machining process that determines the machining time. At constant depth and width of cut, higher cutting velocity results in lower cutting time and vice-versa. In this study, a conservative value for cutting velocity ($V_c$) of 71 m/min is considered based on the recommended cutting velocity of 120 m/min for machining of low-carbon steels [52]. The machining stage (processing in the case of pure CNC milling approach and post-processing in cases of WAAM and SLM) is an important contributor to environmental impact and production cost. The electricity consumed in the pure CNC milling approach is responsible for 19 % of its environmental impact. Also, the cutting time is directly proportional to its machine and labour costs. Similarly, for WAAM and SLM approaches, the post-processing phase accounts for 30 % and 9 %, respectively of their overall environmental impacts. The post-processing step is responsible for 66 % and 25 % of the unit production cost for the WAAM and SLM approaches, respectively. Therefore, the effect of cutting velocity on the environmental and economic impacts of each approach is also studied. The cutting velocity is varied in the range of 71 m/min to 121 m/min, keeping other cutting parameters constant. As the cutting velocity is increased from 71 m/min to 121 m/min, the overall environmental impacts of all 3 approaches are decreased (see Fig. 17). The environmental impact of WAAM decreases from 197 mPts to 175 mPts, for CNC milling it decreases from 496 to 462 mPts, and for SLM it decreases from 663 mPts to 641 mPts. As the cutting velocity increases, the cutting power also increases but the energy consumed in the cutting process decreases due to a reduction in cutting times. Hence, a small reduction in the environmental impact for all 3 approaches is seen. Similarly, the production cost for each approach also decreases due to a decrease in cutting times resulting from an increase in cutting velocity (refer to Fig. 18). As the cutting velocity is increased from 71 m/min to 121 m/min, the unit production cost for pure CNC milling decreases from 145 € to 95 €, for WAAM it decreases from 133 € to 102 €, and for SLM it decreases from 339 € to 307 €. For cutting velocities lower than 96 m/min, WAAM is the most cost-efficient option, while pure CNC milling is the most cost-efficient option for cutting velocities above 96 m/min (see "Break-even point 2" in Fig. 18).

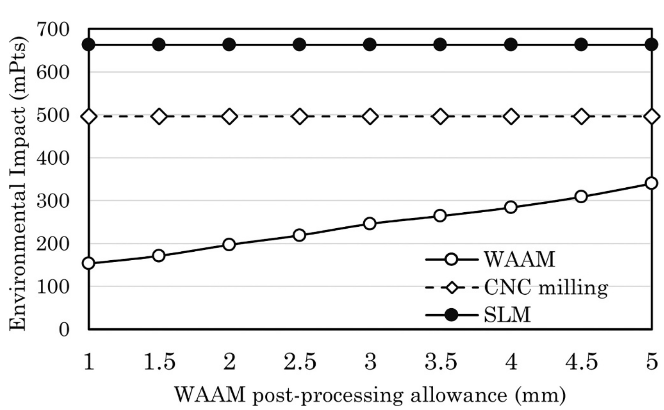


**Fig. 15.** Correlation between environmental impact and post-processing allowance for WAAM.

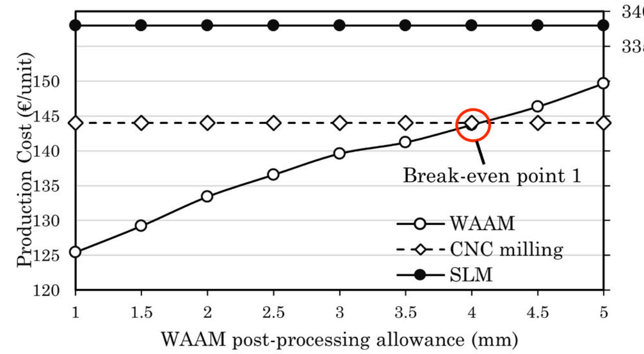


**Fig. 16.** Correlation between unit production cost and post-processing allowance for WAAM.

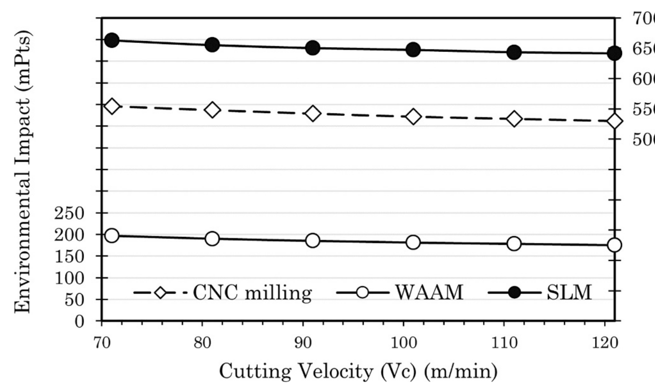


**Fig. 17.** Correlation between cutting velocity and environmental impact.

### 6.5. Uncertainty analysis

The environmental and economic assessment presented in this paper is a data-intensive process. Some inventory data could not be collected experimentally and hence, had to be taken from the relevant literature sources and databases. The inventory data obtained may contain uncertainties, which might have a significant impact on the results of this study. As a result, it is crucial to establish if the environmental impact

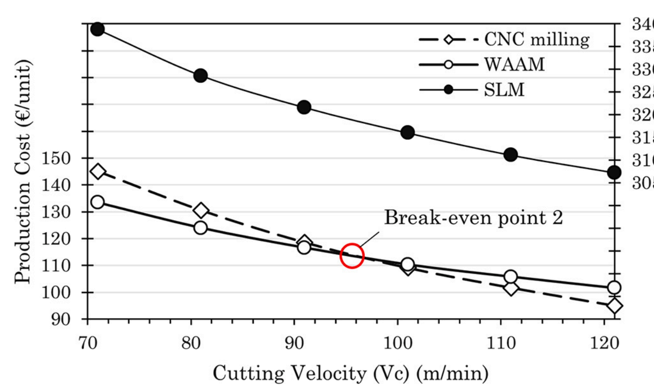


**Fig. 18.** Correlation between cutting velocity and production cost.

and cost of all three processes differ considerably, even when uncertainties in input data are taken into account to understand how the uncertainties in the inventory data affect the environmental effect, an uncertainty analysis is performed. The Monte Carlo Analysis method is used to do the uncertainty analysis in Minitab software. The Monte Carlo method is a mathematical technique that estimates a set of possible outcomes (environmental impact and production cost in this case) and their probability of occurrence by varying the input parameters in their estimated interval of values, as opposed to a predictive model where fixed values of input parameters are used. In a Monte Carlo analysis, a model is simulated for a large number of iterations and in each iteration, a random value for each input parameter is assigned from its range of minimum and maximum values. The result of Monte Carlo analysis is a set of outcomes and probabilities of their occurrence, which aids the decision-making process by taking into account the effect of uncertainties.

In this paper, a normal distribution with a standard deviation (SD) of 10 % of the mean value and a 95 % confidence level is considered for each input inventory in LCA and production cost models. The Monte Carlo analysis was repeated for 10,000 iterations. In each iteration, every input is assigned a random value based on its defined statistical distribution. The results of the Monte Carlo analysis for environmental impact are illustrated in Fig. 19. Here, it is observed that the environmental impact of each approach lies in the following range: pure CNC milling – 419 to 573 mPts, WAAM – 175 to 219 mPts, and SLM – 601 to 726 mPts. Similarly, the results of the Monte Carlo analysis for production cost are depicted in Fig. 20. According to this figure, the unit production cost for pure CNC milling lies between 124 € and 169 €, for WAAM it lies between 107 € and 160 €, and for SLM it lies between 286 € and 390 €.

### 6.6. Limitations and future research directions

The following limitations of this study are realized which can also serve as the directions for future research in this area:

- This study follows a case study approach. Hence, the results of this study are case-specific, particularly in the context of the material and product geometry analyzed. The results will vary for different materials and geometries. Hence, the results of this case study cannot be fully generalized to a wider array of product designs and materials. Future works should analyze the impact of different geometries and materials on the sustainability of additive and subtractive manufacturing approaches.
- This study assumed that the mechanical properties of the propeller made by all 3 approaches is the same. The mechanical properties affect a product's service life. Hence, future works should focus on integrating the mechanical, environmental, and economical assessments of AM products.
- The scope of this study was limited to a cradle-to-gate assessment, excluding the utilization, maintenance, repair, and end-of-life of the marine propeller. WAAM can offer novel repair opportunities in the utilization phase of its product and can extend the service life of a product to multiple life cycles, amplifying the material and energy savings obtained in the production phase [63]. Hence, future works should focus on cradle-to-grave assessments encompassing the entire product life cycle for a comprehensive understanding of a product's environmental and economic behaviour.
- The cutting tool wear during the CNC machining in all 3 approaches and its effect on environmental impact were not included in this study due to the lack of environmental inventories of the cutting tool. The manufacturing of carbide-cutting tools is a material and energy-intensive process. Hence, its effect on the environment should be studied in future works.

The current study is prospective in nature, analyzing an emerging technology like WAAM and comparing it with more matured technologies, namely SLM and CNC milling. AM technologies are continuously evolving. Hence, the possibility of scale-up AM processes and the effect of future developments in AM on the current LCA and LCC results also needs to be foreseen, as suggested by Spreafico et al. [64]. As the raw material is a major driver of environmental impact, improving the material efficiency in both additive and subtractive manufacturing approaches can be a possible future development in the design and manufacture of marine propellers. The application of topological optimization to propeller designs could be a possible future development that could change the current LCA and LCC results and hence, it should be studied in future works. In topological optimization, the distribution of the material in a given domain is optimized while fulfilling a given set of constraints. Therefore, topological optimization can be used to minimize the material required for a given design without compromising its structural integrity [65]. Studies have shown that application of topological optimization along with AM can be used to create lightweight components. Seabra et al. [66] demonstrated a weight reduction of 28 % in an aerospace part by application of topological optimization and used SLM for fabricating the topologically optimized part. Similarly, weight reduction leading to 31 % of material saving of an aeronautical part by a combined application of WAAM and topological optimization was demonstrated by Veiga et al. [67]. The material savings achieved by topological optimization are expected to reduce not only the cradle-to-gate impacts but also the impacts in the use phase due to fuel and energy savings enabled by reduced material, especially for the products like propellers used in transportive applications. Hence, it is expected that with the application of topological optimization, the environmental impact and cost of propeller manufacture by both subtractive and additive technologies could be reduced.

## 7. Conclusions

This study performs a comprehensive cradle-to-gate environmental and economic assessment of pure CNC milling, WAAM, and SLM approaches in manufacturing a steel propeller. The effect of raw material, electricity mix, post-processing material allowance, and cutting velocity on each approach's environmental impact and production cost are also discussed. An uncertainty analysis using the Monte Carlo analysis method is also performed to determine the effect of input data on the outcomes and the probabilities of outcome occurrences. The conclusions of this study are summarized as follows:

- For manufacturing the chosen propeller, WAAM is observed to be the most environmentally friendly and cost-effective approach. WAAM causes an environmental impact nearly 2.5 times lower and is about 8 % cheaper than the pure CNC mailing approach. On the other hand, SLM is the least favourable option, causing an environmental impact nearly 3.4 times higher than WAAM and production cost about 2.5 times more expensive than WAAM.
- The production of primary raw material i.e., steel billet is the major contributor to the environmental impacts of pure CNC milling and WAAM approaches responsible for nearly 76 % and 44 %, respectively of the overall environmental impacts of these approaches. For SLM, the energy consumed during the process is the major contributor, accounting for 36 % of its overall environmental impact.
- The post-processing phase is the major cost driver for the WAAM approach accounting for about two-thirds of its production cost. In pure CNC milling, labour is the most prominent cost driver and contributes to 68 % of the total production cost. For SLM, machine cost is the most significant cost driver responsible for 39 % of its overall production cost.
- Although the WAAM approach has better material efficiency than the pure subtractive approach, its raw material (wire) production is slightly more environmentally intensive than that of the subtractive approach. Hence, from an ecological perspective, WAAM should be

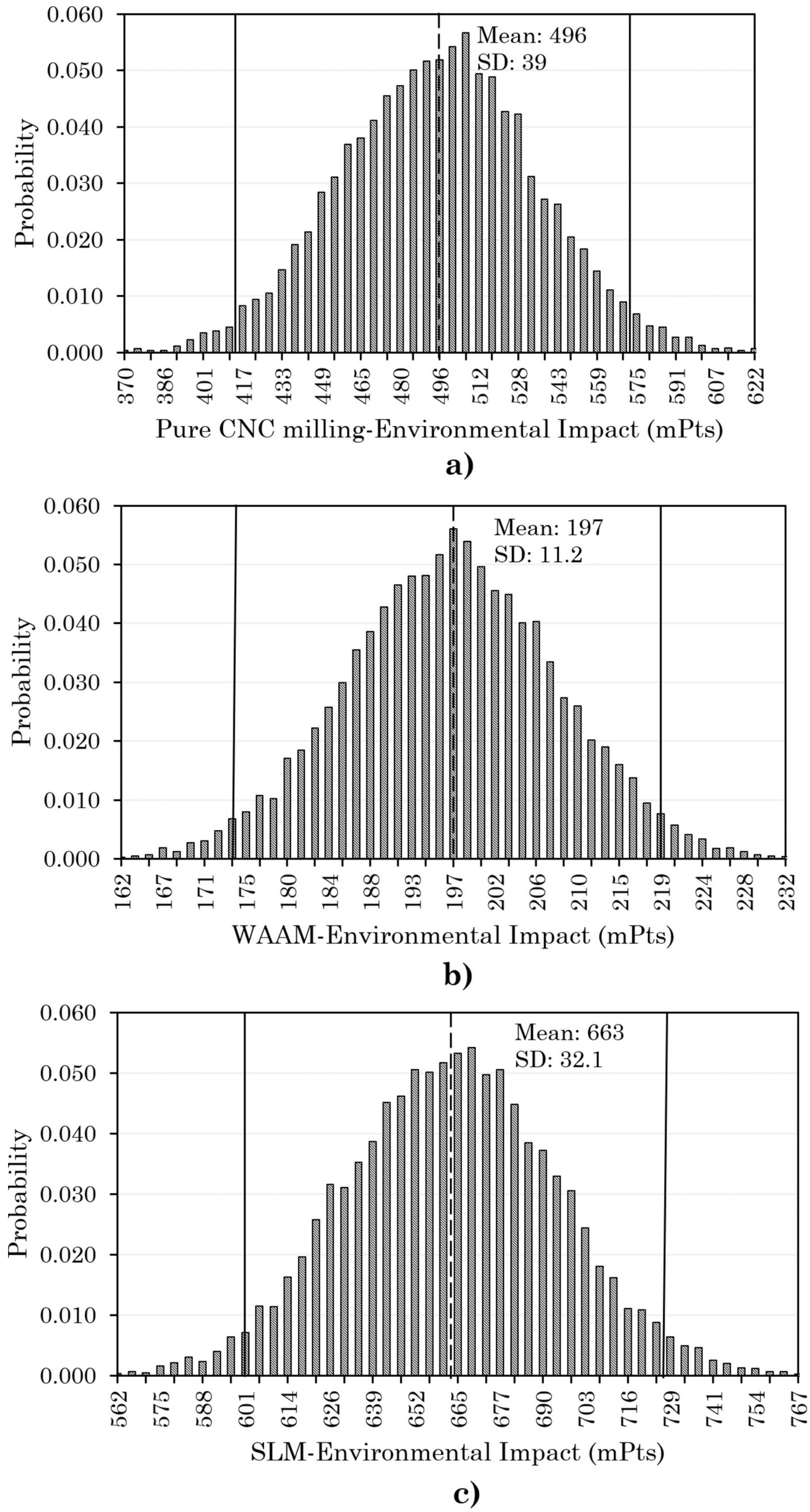


**Fig. 19.** Uncertainty analysis for the environmental impact of a) pure CNC milling b) WAAM c) SLM approaches.

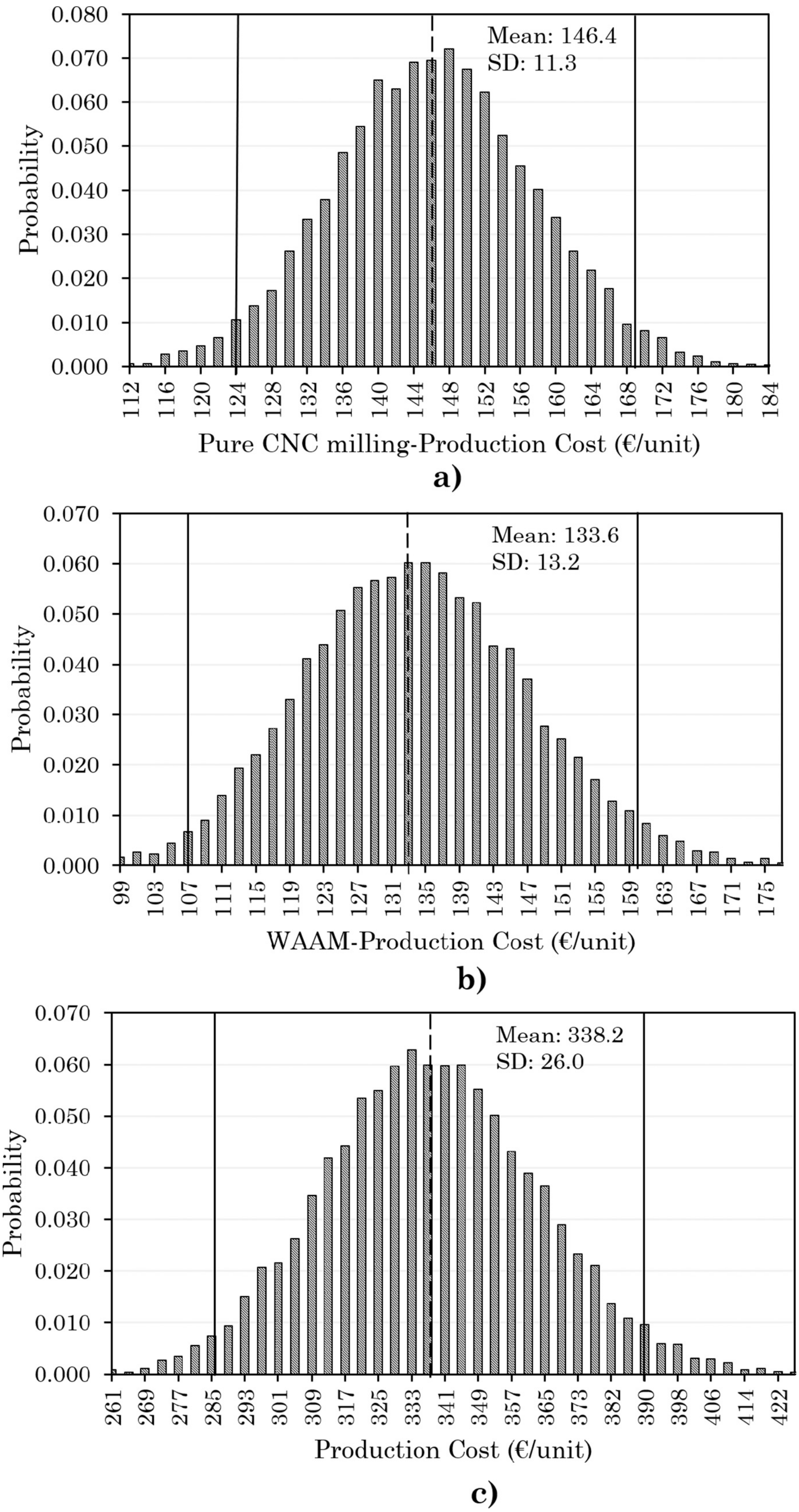


**Fig. 20.** Uncertainty analysis for the production cost of a) pure CNC milling b) WAAM and c) SLM approaches.

adopted only when its material savings outweigh the excess environmental impact arising from its feedstock wire production.

- WAAM is seen to be the most economical approach when its post-processing material allowance is under 4 mm and the cutting velocity is below 96 m/min. For post-processing material allowances above 4 mm and cutting velocities above 96 m/min, pure CNC milling is observed to be the most economical option.
- Adoption of cleaner energy sources can decrease the overall environmental impact of all 3 approaches, especially the SLM approach. For a cleaner electricity mix like the Norwegian mix (where the share of electricity from fossil fuels is <1 %), SLM is seen to be slightly more eco-friendly than the pure CNC milling approach.
- Uncertainty analysis using the Monte Carlo analysis method is performed to study the effect of uncertainty in input data on the environmental impact and production cost. Based on the results of the Monte Carlo analysis, the possible environmental impacts for pure CNC milling, WAAM, and SLM lie in the intervals 419–573 mPts, 175–219 mPts, and 601–726 mPts, respectively. Similarly, the unit production costs for pure CNC milling, WAAM, and SLM methods are in the ranges of 124–169 €, 107–160 €, and 286–390 €, respectively.
- The limitations of this study are (i) The case-specific nature of results; (ii) assuming constant mechanical properties of the product made by each manufacturing approach; (iii) the limited cradle-to-gate scope of the investigation; and (iv) the exclusion of the cutting tool wear and its impact on the environment, due to lack of the cutting tool's environmental inventory data.

Future works should include a wide range of product geometries, materials, and cradle-to-grave system limits. Furthermore, the mechanical characterization of AM produced parts need to be considered along with their environmental and economic assessments and the environmental impact of cutting tool wear must be addressed. The effect of potential future developments such as applying topological optimization to enhance the material-efficiency of WAAM and SLM processes also needs to be explored in depth. WAAM is more beneficial since it uses raw material in the form of wire and can produce complicated components in less time, whereas subtractive techniques require billets of specific dimensions as raw material. As a result, when applied to industrial production, the WAAM technique can facilitate improved stock management. Hence, the environmental and economic effect of WAAM adoption in stock management and the products supply chain must also be studied, WAAM's environmental and economic performance is predicted to improve further as technical advances enable increased dimensional precision, lower surface waviness, low carbon energy, cheaper raw material and machine costs, and enhanced automation reducing the need of constant operator supervision, among other things.

## 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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