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RESEARCH ON SUSTAINABLE ASPECTS IN WIRE ARC ADDITIVE MANUFACTURING OF NICKEL-BASED ALLOY COMPONENTS

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Abstract. In recent decades, metal additive manufacturing (AM) has undergone remarkable advancements and become increasingly significant in manufacturing industries. Among metal AM technologies, wire arc additive manufacturing (WAAM) has great potential for producing medium to large-sized parts and becomes a good choice in the sustainable manufacturing context. This paper aims to analyze the sustainable aspects of WAAM and compare it with CNC machining via the production of an Inconel 625 alloy component. The evaluation is based on life cycle assessment (LCA) and life cycle cost analysis methods. The results demonstrate that WAAM has extremely higher performance in terms of environmental friendliness and economic efficiency versus CNC machining. When the buy-to-fly ratio in CNC machining approach equals 4 and the material utilization factor in WAAM equals 0.8, that the 'WAAM + CNC machining' method is approximately three times more environmentally friendly and 3.2 times more cost-effective compared to 'CNC machining' pathway. This confirms that WAAM combined with CNC machining is an effective approach to meeting current demands for sustainable production.

Keywords: wire arc additive manufacturing, CNC machining, Inconel 625, life cycle assessment, costs, sustainable manufacturing.

1. INTRODUCTION

Metal additive manufacturing (AM) technologies are currently regarded as one of key technologies in Industry 4.0 due to their outstanding advantages, such as enhanced flexibility in design, reduced production cycles, and the ability to produce parts with shapes close to the final product without the need of tooling [1,2]. According to ISO/ASTM 5200:2015 standards, metal AM consists of two main groups: powder bed fusion (PBF) and directed energy deposition (DED). Wire arc additive manufacturing (WAAM) technology is a subset of DED. It stands out as a prominent method suitable for fabricating large-scale parts because of its high deposition rates, efficient material usage, low equipment costs, and environmentally friendly characteristics [3,4].

Many studies have been published on the effectiveness of WAAM compared to various manufacturing methods. Kokare et al. [5] utilized life cycle assessment (LCA) and cost evaluation methods to assess economic and environmental efficiency of three manufacturing approaches - CNC machining, WAAM, and selective laser melting (SLM) – a technology in PBF group. In another study [6], they evaluated the economic and environmental performance of single-wall steel parts manufactured by WAAM compared to Laser-based PBF and CNC milling. Bekker and Verlinden [7] investigated the environmental impacts of steel components fabricated using three different manufacturing processes - WAAM, green sand casting, and CNC milling, employing Life Cycle Assessment (LCA) from raw material extraction to the finished product stage. The results demonstrated that the WAAM process achieved the highest material utilization efficiency. Reis et al. [8] also conducted a comparison between WAAM and CNC milling in terms of environmental impacts throughout the product life cycle analysis, from raw material extraction to manufacturing and disposal. Their findings showed that WAAM is the most ecologically efficient method. Pusateri and Olsen [9] conducted a comparative assessment of the product life cycle (LCA) and life cycle cost (LCC) of components manufactured and repaired by WAAM and traditional manufacturing. The study analyzes environmental impacts and costs throughout the product life cycle. They found that manufacturing through WAAM demonstrated potential advantages from both environmental and economic perspectives.

From the above literature survey, it can be concluded that the WAAM process enables reducing environmental impacts and production costs in manufacturing steel components compared to traditional manufacturing methods [5-9]. However, to date, limited articles have been reported on analyzing the environmental impacts and production costs related to the WAAM process of Inconel 625 components. Therefore, our study aims to prove the advantages of WAAM in manufacture of Inconel 625 parts compared to traditional manufacturing methods. The outcomes contribute to enriching understanding and providing guidelines on the WAAM process of Inconel 625 alloy in terms of economic and environmental performance.

2. METHODOLOGY

2.1. The goal and functional unit definitions

In the current paper, the LCA method is used to evaluate the economic and environmental efficiency of the WAAM process versus the CNC machining. The primary goal of the study is to evaluate economic and environmental efficiency during the manufacturing phase. The material used for this evaluation is Inconel 625 - a nickel-based superalloy. Both methods produced the same product with a mass of 1 kg and the same specifications. An example of the product is introduced in Figure 1. Hence, the functional unit used for the comparison is defined as "the manufacture of a final part from Inconel 625 alloy with a mass of 1 kg".

Figure 1. An example of the flat-blade turbine can be fabricated by both the 'WAAM + CNC machining' and 'CNC machining' approaches.

Based on previous publications on microstructures and mechanical properties of nickel-based alloys [10–12], the tensile properties of Inconel 625 components fabricated by WAAM processes fall in ranges values of casting and forging. Therefore, it can be considered that the final parts produced by both the 'WAAM+CNC machining' and 'CNC machining' methods have comparable mechanical properties and lifespan. The dimensional accuracy and surface quality of the final part according to designed specifications in both the 'WAAM+CNC machining' and 'CNC machining' approaches are achieved by finishing CNC machining operations.

2.2. System boundaries for environmental impact and cost assessment

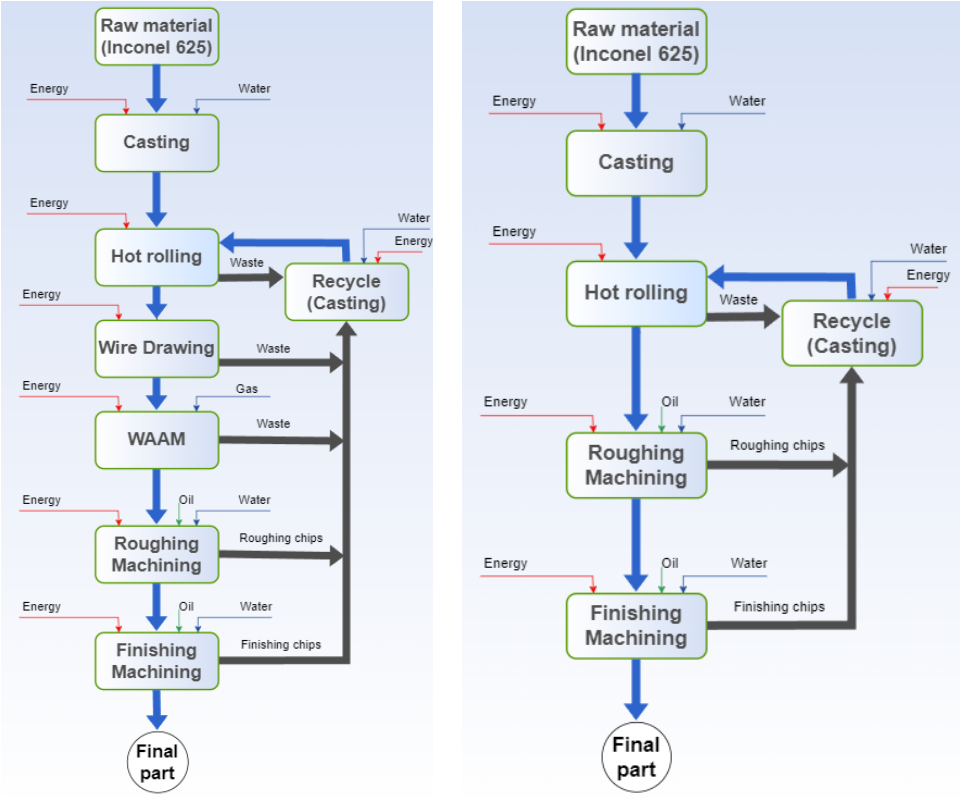
Figure 2 presents the system boundaries for LCA of both the WAAM and CNC machining pathways. The scope of this assessment excludes the usage and end-of-life stages of the product. In the WAAM combined with CNC machining method, Figure 2a, the material utilization factor (ε) is defined as the ratio of the final product volume to the volume of raw materials used. In this study, it is assumed that $\varepsilon = 0.8$, which represents the ratio of the final product volume to the material volume obtained from the welding wire. This means that, in WAAM combined with CNC machining, there are 20% of materials (= 0.2 kg) that should be removed from the part deposited by WAAM to obtain the final part.

In the 'CNC machining' method, Figure 2b, the Buy-to-Fly (BTF) coefficient is defined as the ratio between the workpiece volume and the volume of the final product. In this study, the BTF coefficient corresponding to the part in Figure 1 is about 4. In this case, the mass of chips generated in the finishing milling operation is assumed to be 0.2 kg as in the 'WAAM + CNC machining' method.

In the 'WAAM + CNC machining' method, Figure 2a, the final part is created through a sequence of processes from the raw material, as follows: the billet is achieved from the raw material (Inconel 625) through the casting and hot rolling processes. The welding wire is fabricated from the hot rolled billet through the drawing wire process. Subsequently, the near-net shape part is deposited by WAAM, and the final part is obtained via the roughing and finishing CNC milling operations from the WAAM deposited part.

On the other hand, in the 'CNC machining' method, the final part is achieved from the hot rolled workpiece using roughing milling and finishing milling operations. As in the

‘WAAM + CNC machining’ method, the workpiece used in this pathway is fabricated from casting and hot rolling processes from the raw material (Figure 2b).



(a) WAAM + CNC machining *(b) CNC machining*

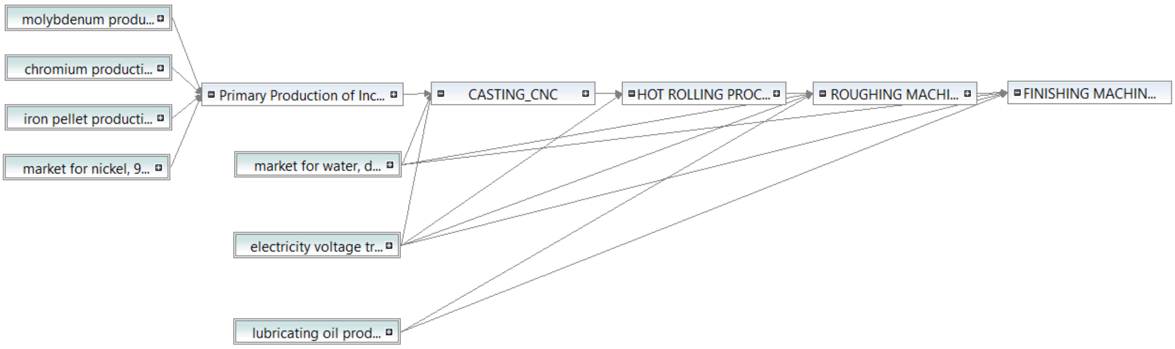
Figure 2. System boundaries for LCA.

2.3. Modelling for environmental impact assessment

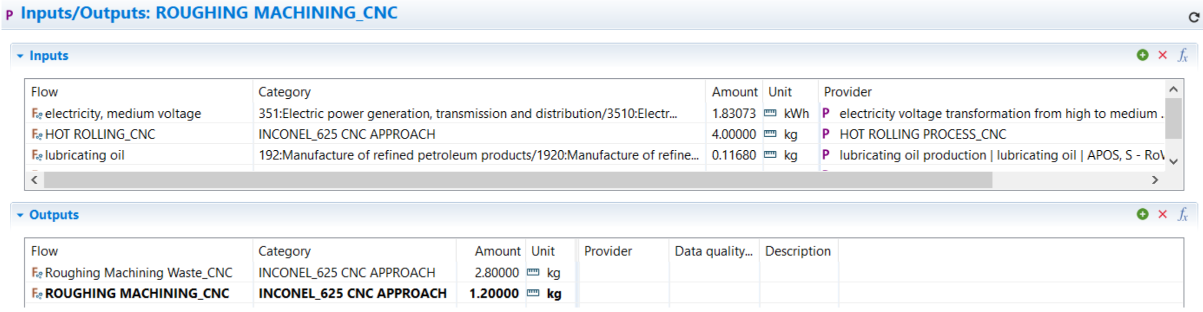
To evaluate the environmental impact, the sequence of processes in both the above manufacturing approaches is modeled in OpenLCA software. This is an open-source software designed for conducting sustainability and life cycle assessments (LCA) and developed by Green Delta in 2007 [13,14]. It offers a range of features to support detailed environmental impact analysis.

In OpenLCA software, each process unit is modeled with defined inputs and outputs (as shown in Figure 3). The inputs include raw materials (or intermediate products obtained from previous manufacturing stages), electricity consumption, consumable materials such as lubricants used in milling operations, and protective gases used in the WAAM process. The outputs consist of the primary products, which are utilized in subsequent processes and waste materials, which are collected and recycled through the casting process to form billets for use in the next product life cycle.

The inputs and outputs of each process unit is calculated based on the mass of the final part, the material utilization coefficient, the specific energy consumption (*SEC*), and so on. The data used for the calculation of process inputs are collected from the previous publications and the experiment (as presented in Section 3). The database used for the environmental impact assessment is Ecoinvent 3.6, which is imported in OpenLCA software.



(a) Modelling of the sequence of processes in the 'CNC machining' pathway



Inputs/Outputs: ROUGHING MACHINING_CNC

Inputs

Flow	Category	Amount	Unit	Provider
electricity, medium voltage	351:Electric power generation, transmission and distribution/3510:Electr...	1.83073	kWh	electricity voltage transformation from high to medium .
HOT ROLLING_CNC	INCONEL_625 CNC APPROACH	4.00000	kg	HOT ROLLING PROCESS_CNC
lubricating oil	192:Manufacture of refined petroleum products/1920:Manufacture of refine...	0.11680	kg	lubricating oil production | lubricating oil | APOS, S - Ro\

Outputs

Flow	Category	Amount	Unit	Provider	Data quality...	Description
Roughing Machining Waste_CNC	INCONEL_625 CNC APPROACH	2.80000	kg			
ROUGHING MACHINING_CNC	**INCONEL_625 CNC APPROACH**	**1.20000**	**kg**			

(b) Modelling of inputs and outputs of roughing machining in the 'CNC machining' pathway

Figure 3. An example of modeling manufacturing processes in OpenLCA software.

3. LIFE CYCLE INVENTORY

3.1. Primary production of Inconel 625 alloy

The primary manufacturing processes, including raw material selection, melting, casting, hot working, and final billet processing. Firstly, high-purity raw materials, including Ni, Cr, Mo, Nb, Fe, and trace elements such as Ti and Al are selected. These elements are carefully weighed and blended to achieve the specified chemical composition, ensuring uniformity in the final alloy structure. Secondly, vacuum induction melting, followed by vacuum arc remelting are performed, and ingots of Inconel 625 alloy are obtained by casting. Finally, hot working processes such as forging and rolling are performed to achieve desired billet dimensions.

3.2. Casting and hot rolling processes

The billet used in both the 'WAAM + CNC machining' and 'CNC machining' methods are manufactured from the same Inconel 625 material, utilizing the outputs of casting and hot rolling processes. The specific energy consumption (*SEC*) for casting and hot rolling was sourced from the "Idemat 2024" database [15]. The *SEC* values for casting and hot rolling process of Inconel 625 are 2.89 kWh/kg and 0.98 kWh/kg, respectively. The total energy consumption in casting and hot rolling process is calculated based on the *SEC* value and the material volume required at each process. The material utilization coefficients employed in the continuous casting and hot rolling processes are 0.9 and 0.95, respectively, as presented in Table 1. The material loss for the continuous casting process is assumed to be 10%, while for the hot rolling process, this coefficient is assumed to be 5%.

Table 1. Material Utilization Coefficients and quantities in two manufacturing methods.

Material or process	Material Utilization Coefficients [7]	Quantities (kg) (WAAM + CNC)	Quantities (kg) (CNC)
Inconel 625	-	1.59	4.68
Continuous casting	0.9	1.43	4.21
Hot rolling	0.95	1.36	4
Wire drawing	0.92	1.25	-
WAAM	0.98	1.225	-
Rough milling	-	1.2	1.2
Fine milling	-	1	1
Recycling	0.9	0.39	2.89

3.3. Rough and fine CNC machining process

In the ‘WAAM + CNC machining’ method, roughing and finishing milling operations are carried out after the WAAM deposition process. For the ‘CNC machining’ pathway, roughing and finishing milling operations are performed directly on the workpiece after the hot rolling stage to produce the final product. These operations are executed on a 3-axis CNC milling machine (Mori Seiki Dura Vertical 5500). The cutting tool for roughing milling operations has a diameter of 15 mm, while the one for finishing milling operations has a diameter of 8 mm. The specific energy consumption (*SEC*) of the CNC milling process is referenced from the document [16], with a reported accuracy of $R^2 = 0.924$. During machining, a lubricating solution consisting of water and lubricating oil is used, with a consumption loss ratio of 0.238 g/s and 0.042 g/s, respectively [17]. Table 2 provides the parameters of the CNC milling process. *MRR* (cm^3/s) presents the material removal rate calculated from cutting parameters by Eq (1):

$$MRR = \frac{a_r \times a_p \times V_c \times f_z \times z}{60 \times \pi \times D} \tag{1}$$

where a_r is radial depth of cut, a_p is axial depth of cut, V_c is cutting speed (m/min), f_z is the feed per tooth (mm/tooth), z is number of teeth, and D is diameter of cutting tool (mm).

In this study, a 15 mm-diameter flat-end mill and an 8 mm-diameter flat-end mill are used for roughing and finishing operations, respectively. Based on the calculation, *MRR* and *SEC* in roughing milling and fine milling are shown in Table 2.

Table 2. Milling parameters, specific energy consumption, and lubricant loss rate in machining.

Parameter	Rough milling	Fine milling
Cutting speed: V_c (m/min)	40	60
Feed per tooth: f_z (mm/z)	0.075	0.07
Radial depth of cut: a_r (mm)	11.25	6
Axial depth of cut: a_p (mm)	1	0.25
Material removal rate: *MRR* (cm^3/s)	0.048	0.017
Number of teeth (z)	4	4
SEC (kJ/cm^3)	$SEC = 2.953 + 2.019/MRR$ [16]	
Water loss rate (g/s)	0.238 [17]	
Oil loss rate (g/s)	0.042 [17]	

3.4. Wire drawing and WAAM process

The Inconel 625 wire used in the WAAM process is produced through the wire drawing process, serving as an input material for the WAAM deposition. Data utilized in the WAAM process is sourced from ‘Ecoinvent 3.6’ and ‘Idemat 2024’ database [15]. Waste materials generated during the wire drawing and WAAM processes primarily result from splashing during deposition and leftover wire cut-off after completing the WAAM process. The *SEC* in WAAM is 0.88 kWh/kg with an arc source power of 4 kW, as reported in [18]. The WAAM process uses 100% Argon gas with a consumption rate of 17 L/min [18]. The process parameters of the WAAM process are given in Table 3.

Table 3. Process parameter for WAAM setup.

Parameters	**Values**
Wire-feed rate (*WFS*)	3.8 m/min
Torch travel speed (*TS*)	240 mm/min
Material setting	Inconel 625
Voltage	17.2 V
Wire diameter (*d*)	1.2 mm

The material utilization coefficients applied in the wire drawing and WAAM processes are 0.92 and 0.98, respectively (Table 1). Therefore, the material loss for the wire drawing process is assumed to be 8%, while for the WAAM process, this coefficient is assumed to be 2% due to spatter [7].

3.5. Recycling process

After manufacturing the target product using two different approaches, waste materials from the previous processes were collected and recycled using the continuous casting method and used as input materials for the next cycle. The *SEC* value was obtained from the ‘Idemat 2024’ database, which is 2.89 kWh/kg [15]. In the ‘WAAM + CNC machining’ method, the input materials for recycling were collected from the following stages: roughing machining, finishing machining, WAAM, hot-rolling, and wire drawing. In the ‘CNC machining’ method, the input materials for recycling were collected from the following stages: hot rolling, roughing machining, and finishing machining, as illustrated in Figure 2. According to the calculation, the amount of waste material to be recycled from the ‘WAAM + CNC machining’ and the ‘CNC machining’ are 0.39 kg and 2.89 kg, respectively. Additionally, the consumed water rate for the cooling during the recycling is 155 L/kg [19]; thus, 508.4 liters of water is consumed in this process.

3.6. Life cycle costs

The research calculates product costs by considering various factors: material usage, machine operating, labor, and consumables such as electricity, lubricating oil, water, and protective gas. The total production costs of the ‘WAAM + CNC machining’ ($C_{WAAM+CNC}^{Total}$) and ‘CNC machining’ (C_{CNC}^{Total}) methods are calculated by Eq. (2) and (3), respectively.

$$C_{WAAM+CNC}^{Total} = C_{machine}^{(WAAM+CNC)} + C_{electricity}^{(WAAM+CNC)} + C_{labor}^{(WAAM+CNC)} + C_{material}^{(WAAM+CNC)} + C_{lubricant}^{(WAAM+CNC)} + C_{shielding\ gas}^{(WAAM+CNC)} \quad (2)$$

$$C_{CNC}^{Total} = C_{machine}^{(CNC)} + C_{electricity}^{(CNC)} + C_{labor}^{(WAAM+CNC)} + C_{material}^{(WAAM+CNC)} + C_{lubricant}^{(WAAM+CNC)} \quad (3)$$

where $C_{machine}^{(*)}$ is the total machine costs incurred during the fabrication processes on WAAM and CNC machines, $C_{electricty}^{(*)}$ is the total cost of energy consumption of the entire cycle, $C_{labor}^{(*)}$ is the labor costs for operating CNC machining and WAAM processes,

$C_{material}^{(*)}$ is the costs of raw material consumed in both two approaches, $C_{lubricant}^{(*)}$ is the cost of the oil and water consumed during the CNC machining operations, and $C_{shielding\ gas}^{(WAAM+CNC)}$ is the cost related to the shielding gas consumed in the WAAM process. Herein, the index $^{(*)}$ denotes ‘WAAM + CNC’ or ‘CNC’.

Material costs and electricity consumption costs are calculated based on prices from the Vietnamese market and quotes provided by suppliers [10-12]. Inconel 625 (in billet form) is a market-referenced value converted for this study. According to the research literature [21], Inconel 625 (in wire form) is priced at \$47.76/kg. The values for electricity, water, and labor costs are referenced from the Vietnamese market. The CNC machine and WAAM machine costs are derived from [6]. Protective gas (argon cylinder) is preferred from [21]. The detailed breakdown of each cost category is presented in Table 4.

Table 4. Cost categories affecting production costs.

Type of cost	**Price**
Inconel 625 (billet form) [20]	58.90 \$/kg
Inconel 625 (wire form) [21]	47.76 \$/kg
Electricity (in Vietnam) [22]	0.084 \$/kWh
Argon (7m^3 Cylinder) [21]	24.83 \$/cylinder
Water [23]	0.4 \$/m^3
Oil	4 \$/kg
Cost of CNC machine [6]	12.61\$/h
Cost of WAAM machine [6]	6.3 \$/h
Hourly labor cost (in Vietnam)	2.5 \$/h

3.6.1. Machine costs

Machine costs ($C_{machine}^{(*)}$) are the costs for WAAM and CNC machining operations, including the machine tool costs (C_{mct}), maintenance costs (C_{mt}) accounting for 3% of the total machine costs, and tooling costs ($C_{tooling}$) accounting for 2% of the total machine costs. The machine cost per hour (*MCC*) is calculated using Eq. (4):

$$MCC = \frac{C_{mct}+C_{mt}+C_{tooling}}{t_{available}} \tag{4}$$

where $t_{available}$ is the time available for the machines. The machines are assumed to have a lifespan of 7 years, operating 2 shifts per day (8 hours per shift) for 250 days a year [6]. The machines are assumed to be utilized for 90% of the available working time [5]. As a result, $t_{available}$ is equal to 26250 hours. The detailed information on calculating *MCC* in WAAM and CNC machining is presented in Table 5.

In the ‘WAAM + CNC machining’ method, $C_{machine}^{(WAAM+CNC)}$ is calculated by the deposition processing time on the WAAM machine (t_{WAAM}) and the machining time on the CNC machine (t_{CNC}) multiplied by *MCC*, Eq. (5):

$$C_{machine}^{(WAAM+CNC)} = MCC_{WAAM} \times t_{WAAM} + MCC_{CNC} \times t_{CNC} \tag{5}$$

where t_{WAAM} is computed using Eq. (6):

$$t_{WAAM} = \frac{m}{m_w} \tag{6}$$

where m is the mass of Inconel 625 used for deposition (m = 1.25 kg) and m_w presents the deposition mass per minute (kg/min). m_w is calculated using the following formula:

$$m_w = v_w \times \rho = \frac{\pi \times d^2}{4} \times WFS \times \rho \tag{7}$$

Herein, v_w represents the wire feed volume per minute (m^3/min), ρ is density of Inconel 625 ($\rho = 8440\ kg/m^3$), d is the wire diameter ($d = 1.2 \times 10^{-3}$ m), WFS is torch travel speed (WFS = 3.8 m/min), as given in Table 3. As computed, t_{WAAM} and t_{CNC} in $C_{machine}^{(WAAM+CNC)}$ are 0.58 h and 0.41 h, respectively. Thus, $C_{machine}^{(WAAM+CNC)}$ is equal to \$9.95.

Table 5. Calculation of machine cost for WAAM and CNC milling.

Process	Costs				References
	Machine tool cost (C_{mct})	Maintenance cost (C_{mt})	Tooling cost ($C_{tooling}$)	Machine cost (MCC)	
WAAM	\$315150	\$9353	\$6187	12.61 \$/h	[6]
CNC	\$157575	\$4727	\$3151	6.3 \$/h	[24]

In the 'CNC machining' method, $C_{machine}^{(CNC)}$ is computed based on the machining time on the milling CNC machine (t_{CNC}), as Eq. (8):

$$C_{machine}^{(CNC)} = MCC_{CNC} \times t_{CNC} \tag{8}$$

As calculated, t_{CNC} in $C_{machine}^{(CNC)}$ is equal to 2.33 hours and MCC_{CNC} is equal to 6.3 (\$/h). As a result, $C_{machine}^{(CNC)}$ is equal to \$20.46.

3.6.2. Electricity costs

This category includes electricity costs in all the processes in Table 6. These costs are calculated based on quotations from manufacturers in the Vietnamese market [22]. Electricity cost is the product of electricity consumed per product (e_{part}) and cost of 1 kWh electricity (EC_{1kWh}):

$$C_{electricity} = e_{part} \times EC_{1kWh} \tag{9}$$

As a result, $C_{electricity}^{(WAAM+CNC)}$ and $C_{electricity}^{(CNC)}$ have values of \$0.68 and \$2.34, respectively.

3.6.3. Labor costs

This category includes the expenses associated with operators performing various tasks in each manufacturing process, such as preparation, setup, machining, and cleaning. Labor costs are calculated by multiplying the hourly labor rate (LC_{1h}) by the total time required to manufacture the product (t_{labor}). The calculation follows the formula:

$$C_{labor} = LCR_{1h} \times t_{labor} \tag{10}$$

where LCR_{1h} is the hourly labor cost, LCR_{1h} = 2.5 \$/h in Vietnam (Table 4), t_{labor} is the working time of operators. t_{labor} = 0.66 hours in the 'WAAM+CNC machining' and 2.33 hours in the 'CNC machining' method.

Table 6. Energy consumed in each process (kWh).

Process	**WAAM + CNC machining**	**CNC machining**
Casting	4.6	13.54
Hot rolling	1.4	4.13
Wire drawing	0.38	-
WAAM	1.1	-
Roughing machining	0.04	4.17
Finishing machining	0.82	0.81
Recycling	1.25	9.29
Total (kWh)	**9.59**	**31.94**

3.6.4. Material costs

Material costs ($C_{material}$) is determined by calculating the mass of materials required for both the 'WAAM+CNC machining' method and 'CNC machining' method. This is done by multiplying the mass of Inconel 625 consumed ($m_{material}$) by its cost per kilogram (MC_{1kg}). The material costs are referenced from the manufacturer's quotation [20] for Inconel in block form and from research [21] for Inconel wire material. The product cost is calculated using the following formula:

$$C_{material} = m_{material} \times MC_{1kg} \tag{11}$$

According to the calculation results from Table 1, the mass of Inconel 625 used in the 'WAAM+CNC machining' method is 1.59 kg, with the price of Inconel in wire form being \$47.76. As a result, $C_{material}^{(WAAM+CNC)}$ = \$75.9. Similarly, the mass of Inconel 625 in billet form consumed in the 'CNC machining' method is 4.68 kg, and the price is 58.9 \$/kg. Thus, $C_{material}^{(CNC)}$ = \$275.56.

3.6.5. Lubricant costs

This category includes the costs of oil and water used in the CNC milling process. These costs are calculated based on quotations from manufacturers in the Vietnamese market [23]. Lubricant cost is calculated by multiplying the amount of oil and water used and their cost per unit.

$$C_{lubricant} = m_{oilLoss} \times MC_{oil\_1kg} + m_{waterLoss} \times MC_{water\_1kg} \tag{12}$$

The water and oil loss rates are 0.238 g/s and 0.042 g/s, respectively. The total CNC machining time is 0.41 hours for the 'WAAM+CNC machining' method and 2.32 hours for the 'CNC machining' method, respectively, with water and oil consumption values of 0.015 kg and 0.003 kg. Consequently, the lubricant cost is \$1.53 for the 'WAAM+CNC machining' method and \$2.16 for the 'CNC machining' method.

3.6.6. Shielding gas costs

In the 'WAAM+CNC machining' method, the deposition time (t_{WAAM}) is 0.25 hours, and the gas flow rate (v_{gas}) is 17 L/min. The amount of Argon gas consumed during the deposition process is calculated using the formula below:

$$C_{shielding\ gas}^{(WAAM+CNC)} = \frac{v_{gas} \times t_{WAAAM} \times 60 \times c_{cylinder}}{v_{cylinder} \times 1000} \tag{13}$$

where $c_{cylinder}$ is the cost of 7 m^3 argon cylinder from Table 4, $v_{cylinder}$ is the volume of the argon cylinder (m^3). $C_{shielding\ gas}^{(WAAM+CNC)}$ is calculated as about \$2.11.

According to the calculated results, the total cost of manufacturing the final product by the ‘WAAM+CNC machining’ method is \$92.79 while the total cost for the ‘CNC machining’ method is \$306.35. A detailed breakdown of the component costs is provided in Table 7.

Table 7. Component costs of each processing method.

Type of cost	**WAAM + CNC machining**	**CNC machining**
Cost of Electricity (\$)	0.81	2.34
Cost of machine (\$)	9.95	20.47
Cost of lubricant (\$)	1.53	2.16
Cost of Shielding gas (Argon) (\$)	2.11	0
Cost of labor (\$)	2.49	5.82
Cost of material (\$)	75.90	275.56
Total (\$)	**92.79**	**306.35**

4. RESULTS AND DISCUSSION

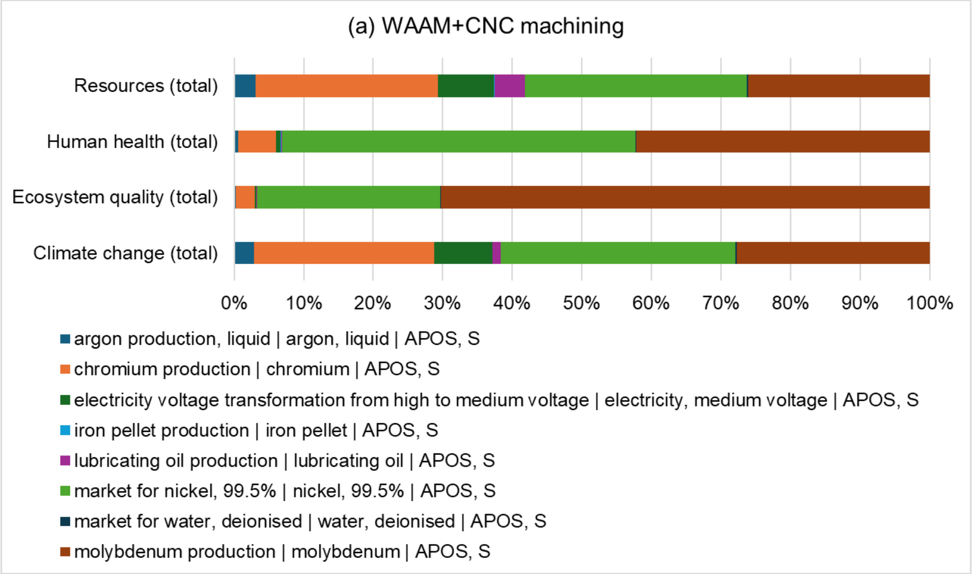
4.1. Evaluation and comparison in environmental impacts

All data from the two approaches are modeled using the OpenLCA software, an open-source software designed for analyzing and assessing environmental impact, economic efficiency, and social impact [13,14]. The evaluation method applied is IMPACT 2002+ (Endpoint), a tool integrated into the OpenLCA software. This method assesses the environmental impact across four main categories from Life Cycle Inventory (LCI): “climate change”, “ecosystem quality”, “human health”, and “resource”.

Figure 4 shows the process contribution to environmental impacts related to both the ‘WAAM and ‘CNC machining’ pathways. It is revealed that in both the ‘WAAM + CNC machining’ and ‘CNC machining’ approaches, the primary production of Inconel 625 alloy from basic metals, including nickel, chrome, molybdenum, and iron contributes the most environmental impacts in all categories (“climate change”, “ecosystem quality”, “human health”, and “resource”), followed by the electricity consumption and lubricant oil production, respectively. In the ‘WAAM + CNC machining’ method, the argon production process also reveals a remarkable amount of environmental impact, especially in the categories of “Resources” and “Climate change”. Similarly, the lubricating oil production exhibits significant contribution to environmental impact in “Resources” and “Climate change” categories.

When comparing the environmental impacts according to the impact categories related to the ‘WAAM + CNC machining’ and ‘CNC machining’ method, it is evident that the ‘WAAM + CNC machining’ exhibits a significantly lower environmental impact level (Figure 5), indicating that the ‘WAAM + CNC machining’ method is more friendly to the environment than the ‘CNC machining’ method. Notably, the ‘CNC machining’ has the greatest effect on human health with a score of nearly 0.14 points, whereas the ‘WAAM + CNC machining’ accounts for only about 0.05 points.

The reasons are because the manufacture of the final part by the ‘CNC machining’ method consumed a remarkably higher volume of raw materials (i.e., Inconel 625 alloy). As shown in Table 1, to produce 1 kg of the final part, the amount of raw Inconel 625 alloys consumed in the 'WAAM + CNC machining' is 1.59 kg, while the 'CNC machining' method consumed 4.68 kg. Moreover, the electricity consumption in the 'CNC machining' pathway is also significantly higher than that in the 'WAAM + CNC machining' (31.94 kWh vs. 9.59 kWh, Table 6). Lastly, the lubricant oil consumed in the 'CNC machining' pathway is higher, leading to generate higher levels of environmental impact in the "Human health" category.



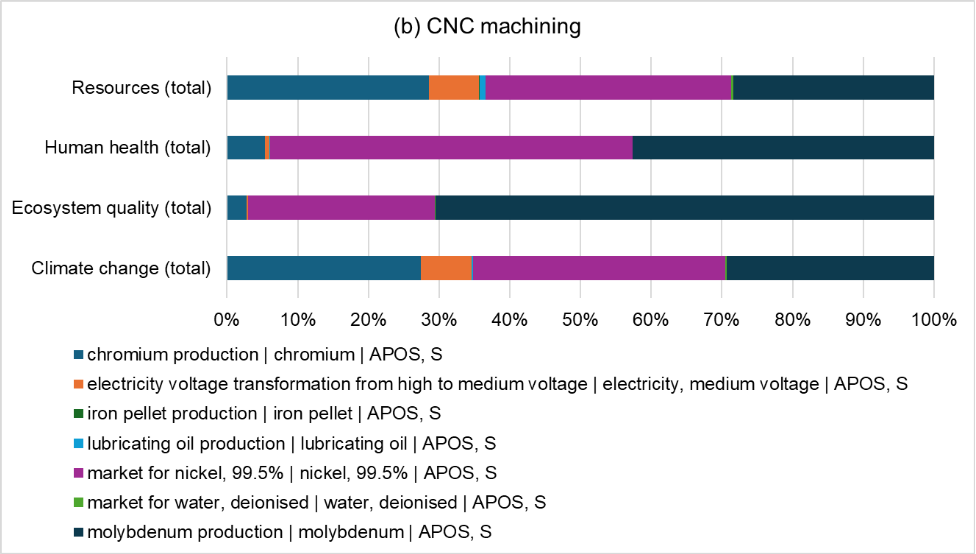


Figure 4. Process contribution to environmental impacts modelled in OpenLCA software for (a) 'WAAM+CNC machining' and (b) 'CNC machining'.

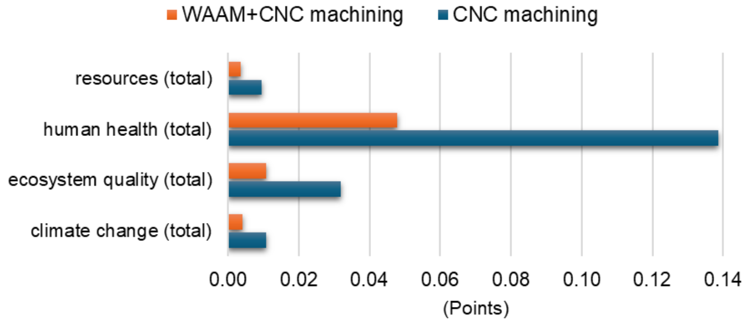


Figure 5. Impact score of each factor on the environment.

4.2. Comparison in production costs

From Figure 6, it is evident that the material cost constitutes the highest proportion compared to other cost components in both the studied methods. In the 'WAAM+CNC machining' method, this cost is $75.9, accounting for 82% of product value. On the other hand, the material cost in 'CNC machining' is $275.6, accounting for 90% of the product value. Comparing the two methods in terms of costs, it is clear that the material cost of the 'CNC machining' method is 3.6 times higher than that of the 'WAAM + CNC machining' method.

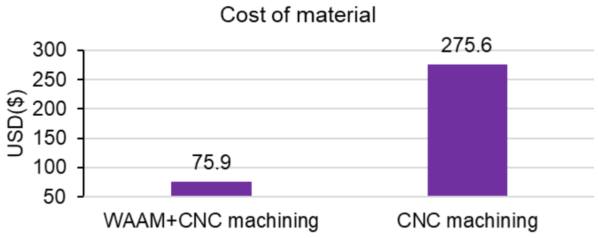


Figure 6. Comparison of material costs between the two methods.

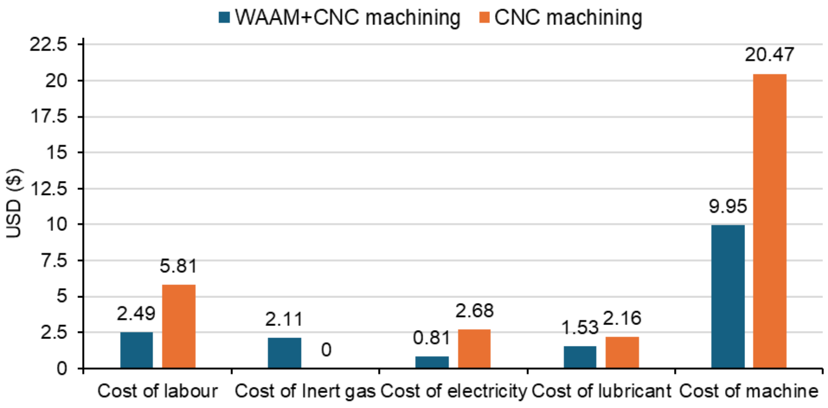


Figure 7. Element costs in the two methods.

As shown in Figure 7, it can be observed that the costs associated with the 'CNC machining' method are also higher compared to the 'WAAM + CNC machining'. In addition to material costs, machine costs represent the second largest component in the total product value ($9.95 in the 'WAAM + CNC machining' vs. $20.47 in the 'CNC machining). The sum of labor cost, lubricant cost, inert gas cost, and electricity cost for the 'WAAM + CNC machining' method is $6.94, whereas that sum in the 'CNC machining' is $10.65.

The economic and environmental efficiency of the ‘WAAM + CNC machining’ pathway primarily stems from its material-saving advantages during the rough machining process and reduced the electricity consumption in both the CNC machining and recycling stages. In the ‘CNC machining’ pathway, a substantial amount of chips is generated, resulting in higher electricity consumption in machining and recycling stages. Conversely, the WAAM process in ‘WAAM + CNC machining’ shapes the part geometry that closely resembles the final product, thus significantly reducing the material volume required for machining compared to the ‘CNC machining’. Given that Inconel 625 alloy is a high-cost material, minimizing the amount of waste directly contributes to a substantial reduction in product costs. This highlights the superior energy efficiency of the ‘WAAM + CNC machining’ method.

5. CONCLUSIONS

This paper evaluates the economic and environmental efficiency of the WAAM process combined with CNC machining through fabricating a final part of 1kg Inconel 625 alloy. The evaluation uses the LCA model and cost analysis. The OpenLCA software, ecoinvent 3.6 database, and IMPACT 2002+ (Endpoint) method were used for modelling environmental impacts related to the fabrication of the final part. The results highlight that the ‘WAAM + CNC machining’ method is approximately three times more environmentally friendly and 3.2 times more cost-effective compared to ‘CNC machining’ pathway. These outcomes demonstrate that the WAAM technique combined with CNC machining (for finishing operations) offers significant advantages in both economic and environmental aspects when the BTF ratio equals to 4 and the material utilization factor $\varepsilon = 0.8$.

In future work, the effects of the part shape and geometry on the comparison results will be investigated. By varying the material utilization factor (ε) value in the “WAAM + CNC machining” approach and the Buy-to-Fly (*BTF*) coefficient in “CNC machining” approach, we can determine the benefit area of each manufacturing approach in terms of economic and environmental performance.

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