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Environmental and Economic Comparison of Wire and Swarf in a Novel Additive Manufacturing Technique for Aerospace Applications

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Abstract. In the context of sustainable manufacturing, the choice of materials and processes significantly impacts the environmental footprint and overall costs of additive manufacturing (AM). This study investigates the use of wire versus swarf as feedstocks in a novel additive manufacturing technique process and compares these methods with Wire Arc Additive Manufacturing (WAAM). Specifically, the carbon footprint (CO_2 emissions), energy consumption, and cost implications of each approach are evaluated. The findings reveal that, while wire-based methods are commonly employed for their precision and quality, swarf recycled from manufacturing waste offers substantial environmental benefits by reducing energy consumption and lowering carbon emissions. Moreover, the cost comparison shows that swarf can reduce overall production costs, providing a more cost-effective solution, especially in high-volume aerospace applications. This work highlights the potential of integrating swarf into WAAM processes as a sustainable alternative, offering insights into optimizing both environmental performance and economic viability in AM. The results are expected to contribute to the advancement of more sustainable and economically viable additive manufacturing strategies.

Keywords: Sustainable Manufacturing, Additive Manufacturing, Swarf Feedstock, Aerospace Manufacturing, Environmental and Economic Impact

1 Introduction

Titanium alloys are widely employed in aerospace and other high-performance sectors due to their excellent strength-to-weight ratio, corrosion resistance, and high-temperature performance. However, these benefits come at a significant environmental and economic cost. Primary titanium extraction and processing are energy intensive, and traditional subtractive manufacturing routes exhibit poor material efficiency. For many aerospace components, as much as 80–90% of the starting ingot mass is lost as machining swarf [1]. Conventional recycling of swarf through remelting and casting into ingots is possible, but it is highly energy demanding and undermines the sustainability gains sought in lightweight design [1]. Consequently, identifying more resource-efficient pathways for titanium reuse and part production is a critical research priority.

Additive manufacturing (AM) offers a promising alternative by enabling near-net-shape production and reducing material waste compared to machining. Life cycle assessment (LCA) studies have consistently shown that AM can improve resource efficiency, though trade-offs in energy consumption and process impacts remain [2,3]. Within AM, Wire Arc Additive Manufacturing (WAAM) has emerged as a cost-effective and scalable process for large titanium components due to its high deposition rates and suitability for structural applications [4,5]. Yet, the sustainability of WAAM is strongly constrained by its reliance on titanium wire feedstock. Multiple studies have reported that wire production dominates both the energy demand and the global warming potential (GWP) of WAAM parts [4,6–8]. This dependence on virgin wire also drives up costs, limiting the broader industrial uptake of WAAM despite its technical maturity.

To mitigate these limitations, several research efforts have focused on the recycling and reuse of titanium swarf as an AM feedstock. Powder-based routes, such as hydrogenation–dehydrogenation (HDH) and multistage ball milling, have been developed to convert swarf into powders suitable for laser-based processes, showing promising environmental advantages compared to gas atomization [9]. Solid-state recycling routes, including FAST-forge [10] and continuous extrusion via the Conform process [11], have demonstrated the feasibility of transforming swarf directly into billets or wire, though challenges remain in terms of energy use, product quality, and scalability. Cleaning and pre-treatment of swarf are also crucial: chemical washing, ultrasonic cleaning, and emerging cryogenic methods aim to remove residual contaminants, but each introduces additional environmental and cost trade-offs [12,13]. While these advances highlight the potential of swarf recycling, most studies stop short of directly integrating swarf into AM process chains or benchmarking such approaches against WAAM.

In this context, a new WAAM-based approach is proposed and assessed in this work, referred to as WAAM with Solid Infill (WAAM-SI). This process combines the strengths of conventional WAAM with the resource efficiency of swarf reuse by depositing a skin of virgin titanium wire while filling the bulk core with

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infiltrated and melted recycled swarf. A virgin titanium substrate, common to both processes, provides structural support. This hybrid feedstock strategy reduces the reliance on virgin wire while retaining WAAM's geometric control and surface quality. Despite its potential, no systematic studies have quantified the environmental and economic trade-offs of WAAM-SI compared to conventional WAAM.

The objective of this paper is therefore to conduct a comparative assessment of WAAM-SI and WAAM. A cradle-to-gate LCA is performed to evaluate energy demand and GWP, complemented by an activity-based costing (ABC) analysis to examine process economics. By situating WAAM-SI alongside conventional WAAM in terms of both sustainability and cost, this study addresses a critical gap in the literature and provides insights into the role of swarf as a viable feedstock for large-scale additive manufacturing in aerospace applications.

2 Methodology

This study establishes a systematic framework to compare conventional Wire Arc Additive Manufacturing (WAAM) with a novel WAAM-Solid Infill (WAAM-SI) process that incorporates recycled titanium swarf. In WAAM-SI, 10% of the part mass is deposited as a wire-based skin to ensure surface quality, while the remaining 90% of the core is filled using swarf, complemented by a virgin titanium substrate common to both routes. The methodology integrates process modelling, life cycle assessment (LCA), and cost analysis to capture both environmental and economic performance.

2.1 Additive Manufacturing Processes and Feedstock Preparation

Conventional WAAM was modelled using commercial Ti-6Al-4V wire feedstock, with process parameters (wire feed rate, travel speed, arc current and voltage, layer geometry) varied to represent different deposition rates. WAAM-SI was assessed as a hybrid route, in which swarf was cleaned, consolidated, and used for solid infilling of the part core, while the outer skin was deposited by WAAM.

Both processes were benchmarked against the manufacture of a Ti-6Al-4V titanium aerospace rib demonstrator part (155.6 kg), which defines the functional unit of the study (Figure 1). Material characterisation of swarf (chemical composition, density, morphology, and surface condition) was based on recent literature to ensure comparability with wire-based deposition behaviour.

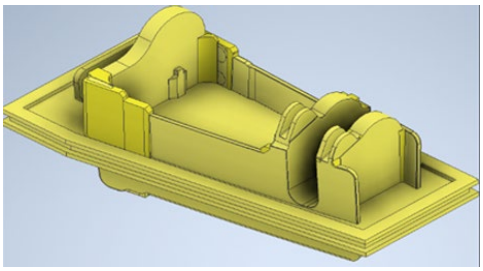


Figure 1 Titanium aerospace rib demonstrator part.

2.2 Environmental and Economic Assessment

A comparative cradle-to-gate life cycle assessment (LCA) was performed following ISO 14040/44 standards. The system boundaries encompassed three main stages: feedstock production, deposition, and post-processing. Feedstock production included the manufacturing of virgin Ti-6Al-4V wire and the collection, cleaning, and consolidation of recycled swarf. Deposition considered both conventional WAAM and the novel WAAM-Solid Infill (WAAM-SI) process, with varying deposition rates for WAAM and different infill percentages for WAAM-SI. Post-processing encompassed all finishing operations required to achieve the final part geometry.

The primary impact category considered was global warming potential (GWP, kg CO_2-eq per kg of part), with cumulative energy demand included as a secondary environmental indicator. Life cycle inventory data were obtained from Ecoinvent and recent literature on WAAM and metal recycling [14,15]. The LCA framework allowed a systematic evaluation of how deposition parameters and infill strategies influence the environmental performance of the manufactured part.

An economic assessment was conducted in parallel, considering feedstock, energy, labor, and equipment costs. The total cost per kilogram of part was calculated as:

$$C_{Total} = C_{Feedstock} + C_{Energy} + C_{Labor} + C_{Equipment} \quad (1)$$

The comparative analysis focused on three key aspects: the influence of WAAM deposition rate on energy consumption and GWP, the effect of WAAM-SI infill rate on material utilization, energy, and carbon footprint, and the trade-offs between environmental and economic performance for both processes. This

methodology provides a robust framework to demonstrate the environmental and economic advantages of WAAM-SI over conventional WAAM, particularly in high-volume aerospace applications.

3 WAAM and WAAM-SI Processes

3.1 Process Maps

The process flows for conventional Wire Arc Additive Manufacturing (WAAM) and the proposed WAAM-Solid Infill (WAAM-SI) process are illustrated in Figures 1 and 2. These maps outline the stages considered in the comparative assessment, covering feedstock production, deposition, and post-processing.

In conventional WAAM (Figure 1), raw material production is followed by rolling and subsequent wire drawing to produce the feedstock. A machined substrate is prepared, and deposition is performed entirely with wire. The component is then subjected to final machining to achieve the required geometry. This sequence reflects the standard industrial practice for large-scale WAAM applications.

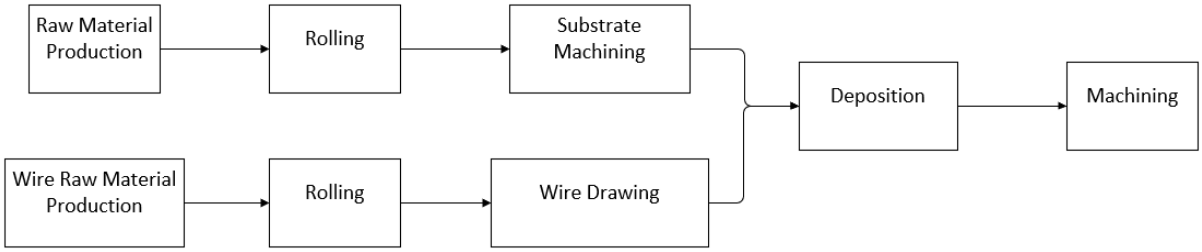


Figure 2 WAAM process map.

In contrast, the WAAM-SI process (Figure 2) introduces a dual-feedstock strategy by integrating recycled swarf into the manufacturing chain. Alongside conventional raw material processing for substrate and wire production, swarf generated from machining is collected, cleaned, and consolidated. The outer skin of the component is deposited using wire feedstock to maintain surface quality, while the core is infilled with swarf through a melting and consolidation stage. Both layers are then finished with final machining operations.

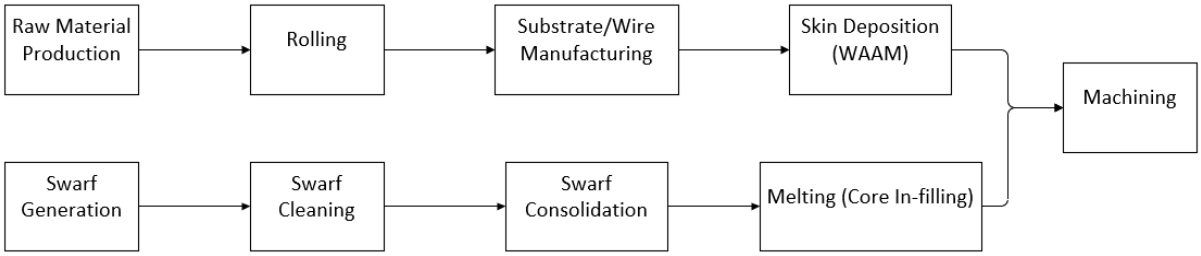


Figure 3 WAAM-SI process map.

The main differences between the two routes lie in the feedstock preparation and deposition stages. While WAAM relies exclusively on virgin wire, WAAM-SI incorporates a circular economy approach by utilizing recycled swarf, thereby reducing demand for virgin wire. This modification is expected to reduce energy consumption, global warming potential (GWP), and material cost, particularly when applied to high-mass aerospace components.

3.2 Inventory Analysis

The life cycle inventory (LCI) provides a detailed breakdown of the material and energy flows for both conventional WAAM and the proposed WAAM-Solid Infill (WAAM–SI) system. Following the cradle-to-gate system boundaries, the inventory accounts for feedstock production, deposition, post-processing, swarf cleaning, and transportation.

The inventory data form the basis for subsequent life cycle impact calculations. Environmental flows (energy consumption, CO_2 emissions) and mass balances were derived using the following relationships:

$$Input\ Material\ Mass\ (M_{in}) = Mass\ Produced\ (M_{prod}) \times Material\ Utilization\ Factor\ (U) \quad (2)$$

$$Energy\ Consumed\ (E_{Cons}) = Mass\ Produced\ (M_{prod}) \times\ Energy\ Intensity\ Factor\ (\in) \quad (3)$$

$$Equivalent\ CO_2\ Emission\ (CO_{2,eq}) = Mass\ Produced\ (M_{prod}) \times CO_2\ Intensity\ Factor\ (\gamma) \quad (4)$$

The input analysis (Table 1) shows that WAAM–SI reduces the requirement for virgin wire compared to conventional WAAM, as only the outer skin of the part is deposited using wire feedstock. The core is produced from recycled swarf, which introduces additional steps such as cleaning and consolidation but significantly reduces reliance on primary ingot and wire production.

Table 1. WAAM and WAAM – SI system inputs.

Process	Input Data	Units	SAM Solid Infill	WAAM
Ingot Production	Energy	MJ	119957.70 [14]	168427.96 [14]
	Cast Ingot	kg	367.40 [14]	515.86 [14]
Hot Rolling (Wire)	Energy	MJ	230.93 [15]	2309.29 [15]
	Cast Ingot	kg	16.49 [15]	164.95 [15]
Wire Drawing	Energy	MJ	1495.15 [15]	14951.52 [15]
	Rolled Rod	kg	15.71 [15]	157.09 [15]
Hot Rolling (Substrate)	Energy	MJ	4912.74 [15]	4912.74 [15]
	Cast Ingot	kg	350.91 [15]	350.91 [15]
Substrate Machining	Energy	MJ	385.81 [16]	385.81 [16]
	Rolled/Forged Plate	kg	334.20 [16]	334.20 [16]
WAAM Deposition	Wire	kg	13.78 [14]	137.80 [14]
	Electricity	MJ	451.23 [14]	4512.34 [14]
	Argon	L	84000 [14]	84000 [14]
Solid Infilling	Energy	MJ	8351.18 [17]	–
	Swarf	kg	127.67 [17]	–
	Argon	L	84000 [17]	–
Coarse Machining	Energy	MJ	275.62 [16]	275.62 [16]
	AM Part/Raw Material	kg	324.26 [16]	324.26 [16]
Finish Machining	Energy	MJ	1437.49 [16]	1437.49 [16]
	Coarse Machined Part	kg	220.65 [16]	220.65 [16]
Swarf Cleaning	Electricity	MJ	111.83 [17]	–
	Dirty Swarf	kg	131.50 [17]	–
	Liquid Nitrogen	kg	19.72 [17]	–
Transportation	Total Weight	kg	603.32 [18]	472 [18]
	Energy	MJ	283.56 [18]	221.84 [18]

The output analysis (Table 2) highlights how swarf generated during machining is partly reclaimed, cleaned, and reused in WAAM–SI, enhancing material circularity. In contrast, conventional WAAM depends exclusively on wire feedstock and produces a higher proportion of wire waste during deposition. Both processes achieve the same final part weight, but WAAM–SI does so with improved feedstock efficiency and lower waste generation.

Table 2. WAAM and WAAM – SI system outputs.

Process	Output Data	Units	SAM Solid Infill	WAAM
Ingot Production	Cast Ingot	kg	367.40 [14]	515.86 [14]
Hot Rolling (Wire)	Rolled Rod	kg	15.71 [15]	157.09 [15]
	Waste	kg	0.79 [15]	7.85 [15]
Wire Drawing	Finished Wire	kg	13.78 [15]	137.80 [15]
	Waste	kg	1.93 [15]	19.29 [15]

Hot Rolling (Substrate)	Rolled/Forged Plate	kg	334.20 [15]	334.20 [15]
	Waste	kg	16.71 [15]	16.71 [15]
Substrate Machining	Finished Substrate	kg	189.16 [16]	189.16 [16]
	Swarf	kg	145.04 [16]	145.04 [16]
WAAM Deposition	Deposited Part	kg	–	324.26 [14]
	Wire Deposited	kg	13.51 [14]	135.10 [14]
	Wire Wasted	kg	0.27 [14]	2.70 [14]
Solid Infilling	Finished Part	kg	–	–
	Waste	kg	–	–
Coarse Machining	Coarse Machined Part	kg	220.65 [16]	220.65 [16]
	Swarf	kg	103.62 [16]	103.62 [16]
Finish Machining	Finished Part	kg	155.6 [16]	155.6 [16]
	Swarf	kg	65.05 [16]	65.05 [16]
Swarf Cleaning	Clean Swarf	kg	127.67 [17]	–
	Waste Swarf	kg	3.83 [17]	–

Overall, the inventory analysis highlights three fundamental differences between the two systems. WAAM–SI achieves greater feedstock efficiency by reducing the need for virgin ingot and wire through the partial substitution of swarf in the part core. This introduces a shift in energy demand, as additional energy is required for swarf cleaning and consolidation; however, this is balanced by lower energy consumption in wire production. Finally, WAAM–SI enhances material circularity by reintroducing swarf into the process, thereby minimizing waste generation and improving resource efficiency compared to conventional WAAM.

4 Life Cycle and Cost Assessment Results

4.1 Energy and GWP Results

The aim of this study was to evaluate the environmental performance of conventional WAAM and the proposed WAAM-SI process. In WAAM, the reliance on wire feedstock dominates energy demand and emissions, whereas WAAM-SI mitigates this impact by replacing most of the core material with recycled swarf. The figure 4 presented illustrate the distribution of energy consumption and GWP across key process stages, highlighting the areas where reductions are achieved and where minor additional burdens are introduced.

The energy consumption results presented indicate that raw material production is the most energy-intensive stage for both processes, with a markedly higher contribution in WAAM compared to WAAM-SI. For WAAM, wire manufacturing represents the dominant share of process energy, whereas in WAAM-SI this burden is shifted towards the in-filling stage due to the use of recycled swarf. All other stages contribute relatively minor amounts, though they reinforce the different energy distribution profiles of the two routes. The overall results (Figure 4) demonstrate the clear efficiency advantage of WAAM-SI, primarily driven by reduced reliance on virgin wire feedstock.

At a skin–core ratio of 0.1, the Global Warming Potential (GWP) profiles of WAAM and WAAM-SI differ markedly. In WAAM, ingot production and wire manufacturing dominate the emissions profile, reflecting the heavy dependence on virgin feedstock. In contrast, WAAM-SI shifts the main contribution to the in-filling stage, linked to the processing of recycled swarf. Even with this added burden, the total CO_2 emissions remain substantially lower than for WAAM, demonstrating that integrating 90% swarf in the core provides a clear reduction in environmental impact while maintaining process viability.

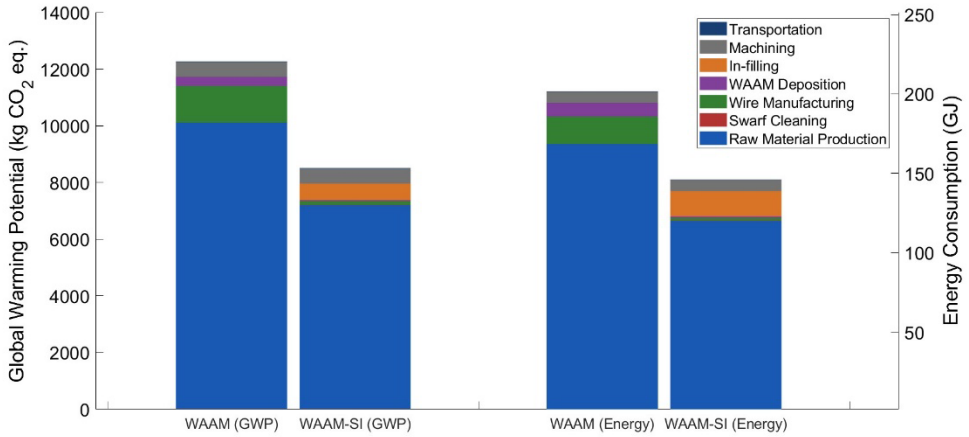


Figure 4 Global Warming Potential (kg CO_2 eq.) and Energy consumption (GJ) breakdown of Wire Arc Additive Manufacturing (WAAM) and Wire Arc Additive Manufacturing Solid Infill (WAAM-SI).

4.2 Comparative Cost Analysis

The comparison between WAAM and WAAM-SI was based on the input assumptions summarised in Table 3. WAAM employed wire as feedstock with varying deposition rates, while WAAM-SI integrated swarf as in-fill material at fixed deposition rates, with wire retained for the skin. Both models accounted for labour cost, electricity and consumables, raw materials and machine cost. These cost calculations were performed using GBP values based on 2024 rates, to ensure the consistency and comparability of the results.

Table 3. Cost Parameters for WAAM and WAAM-SI.

Parameter	WAAM	WAAM-SI
Feedstock	Wire	Wire (skin) + Swarf (in-fill)
Feedstock cost basis	Commercial wire invoice	Commercial swarf invoice
Deposition rate (kg/h)	0.9–4.0	0.33 (baseline) / 1.0 (improved)
Costs considered	Feedstock, energy, gas, machine & labour	Feedstock, swarf cleaning, energy, gas, machine & labour

The cost comparison shows that WAAM is dominated by the high price of wire feedstock, whereas WAAM-SI achieves lower costs by using only 10% wire for the skin and 90% swarf for the core as seen in Figure 5. This material balance is the main driver of the price difference, with the additional virgin titanium substrate contributing equally to both processes.

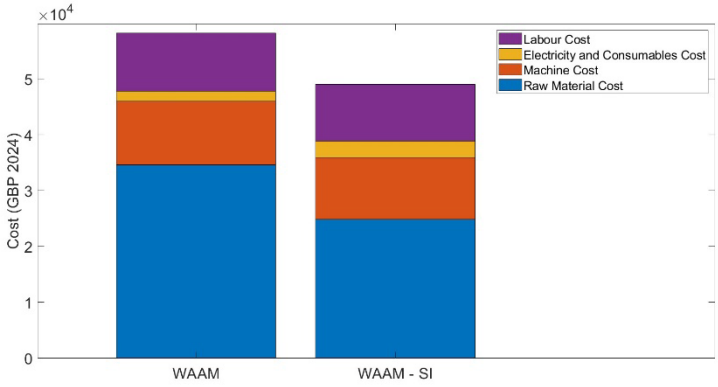


Figure 5 Cost breakdown of Wire Arc Additive Manufacturing (WAAM) and Wire Arc Additive Manufacturing Solid Infill (WAAM-SI).

Figure 6 shows the sensitivity of WAAM-SI economics to the in-fill deposition rate. At low in-fill rates, costs remain high across all skin percentages due to extended build times. As the in-fill rate increases, the total cost decreases sharply, with the greatest savings observed at low skin percentages where swarf dominates the feedstock. At higher skin fractions, the cost advantage diminishes as wire feedstock requirements increase, but improvements in in-fill rate remain the key driver of competitiveness.

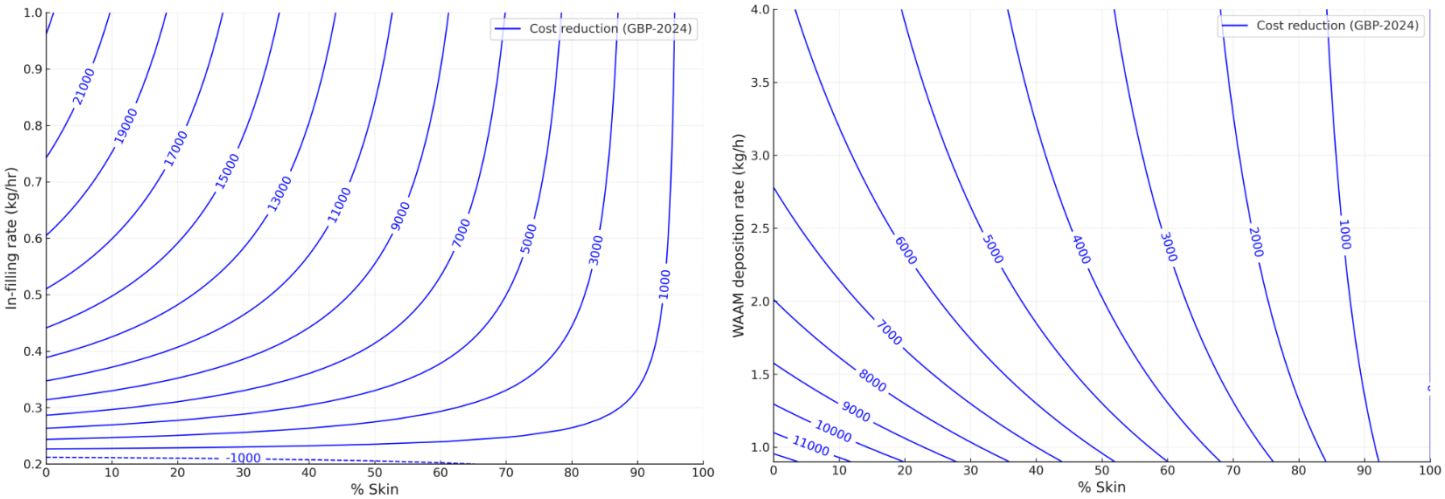


Figure 6 & 7 Cost reduction (GBP) of WAAM-Solid Infill (WAAM–SI) relative to WAAM as a function of skin percentage vs in-filling rate (Fig 6), and vs deposition rate (Fig 7), where 100% skin = WAAM baseline.

Figure 7 illustrates the comparative cost difference between WAAM-SI and conventional WAAM. At lower WAAM deposition rates and low skin percentages, WAAM-SI achieves the largest reductions, highlighting the combined effect of swarf substitution and shorter build times. As WAAM deposition rates increase, the relative advantage of WAAM-SI decreases, but the process still maintains a cost benefit over the investigated parameter space provided in-fill rates are sufficiently high. These results emphasise the trade-off between material substitution and deposition productivity in determining the overall cost competitiveness of WAAM-SI.

Overall, the results show that WAAM-SI can deliver significant cost reductions compared to conventional WAAM when in-fill deposition rates are sufficiently high. While low in-fill rates make the process uncompetitive due to extended build times, moderate improvements unlock the economic benefits of swarf substitution, particularly at lower skin percentages.

5 Conclusions

This study compared the environmental and economic performance of conventional WAAM and the proposed WAAM-SI process. The results show that WAAM-SI achieves significant reductions in both energy consumption and GWP by replacing 90% of the part core with recycled swarf, while retaining 10% wire for the skin and a virgin titanium substrate common to both processes. This material balance is the main driver of the observed improvements, lowering the burden of wire production and shifting the cost and environmental profiles in favour of WAAM-SI. The economic analysis further confirmed that raw material substitution is the dominant factor in cost reduction, with WAAM-SI consistently outperforming WAAM when deposition rates and in-fill strategies are optimised.

Future work will focus on validating the WAAM-SI approach under industrial conditions to confirm the modelling assumptions and capture process variability. In addition, mechanical performance testing is needed to ensure that the swarf–wire hybrid structure delivers the required material properties for high-value aerospace applications. Finally, system-level studies on end-of-life recycling, supply chain integration, and scalability will be undertaken to demonstrate the broader circular economy potential of swarf-based additive manufacturing.

Acknowledgments

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