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Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing

Paolo C. Priarone[a], Emanuele Pagone[b], Filomeno Martina[c], Angioletta R. Catalano[a], Luca Settineri (1)[a,*]

[a] *Department of Management and Production Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[b] *Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, MK43 0AL Cranfield, United Kingdom*
[c] *Welding Engineering and Laser Processing Centre, Cranfield University, Building 46, MK43 0AL Cranfield, United Kingdom*

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ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is a fusion- and wire-based additive manufacturing technology which has gained industrial interest for the production of medium-to-large components with high material deposition rates. However, in-depth studies on performance indicators that incorporate economic and environmental sustainability still have to be carried out. The first aim of the paper has been to quantify the performance metrics of WAAM-based manufacturing approaches, while varying the size and the deposited material of the component. The second aim has been to propose a multi-criteria decision-analysis mapping to compare the combined impacts of products manufactured by means of the WAAM-based approach and machining.

1. Introduction

Wire Arc Additive Manufacturing (WAAM) extends the benefits of layer-by-layer fabrication to medium-to-large parts of low geometrical complexity, while exploiting much higher deposition rates than powder-bed technologies [1]. However, the current limitations, in terms of surface finish and dimensional accuracy of the as-deposited features, still make it necessary to carry out machining processes after WAAM. Therefore, in addition to the technological implications, the overall sustainability of choosing a WAAM-based integrated approach, instead of a conventional one, should be verified, and comparative assessments [2], at different system levels [3], are needed for this purpose. Additive Manufacturing (AM) has in general proved to be beneficial for a reduction of the global warming potential [4]. Nevertheless, the economic and environmental competitiveness of WAAM, in comparison to other manufacturing processes, has only been investigated in a limited number of studies [5,6]. In the present paper, a methodology is applied to compare the performances of WAAM-based additive/subtractive approaches and milling. A cradle-to-gate assessment allows the cumulative energy demand and carbon dioxide emissions of both manufacturing approaches to be quantified. The manufacturing time and the product cost are assumed as productivity and economic metrics, whereas the results of tensile tests, carried out on WAAM-ed and parental materials, are considered as a proxy of the in-use material performance. A comparative multi-criteria mapping is then proposed to combine the conflicting metrics. The aim of this research has been to contribute towards the development of tools that may be used to select sustainable manufacturing approaches while understanding their trade-offs.

2. Materials and methods

Three medium-to-large industrial components, characterised by different geometrical shapes and made of different materials, have been considered, as detailed in Table 1. In order to produce the components, which are conventionally manufactured by means of material removal processes from massive workpieces, two different WAAM system configurations were used, both based on anthropomorphic 6-axis Kuka robots for the provision of motion. The first system relies on a plasma-arc power source (water cooled), and has a shielding device for the local supply of an inert gas atmosphere. This system was used to deposit two components: (*i*) a titanium bracket of about 8 kg, which is generally found on the airframes of civil aircraft; and (*ii*) a 5-metre-long ER70s-6 steel cantilever beam for architectural applications. Given the length of the latter, a linear slide was used to provide an additional motion axis to the robotic arm (as shown in Fig. 1). The second setup relies on Cold Metal Transfer (CMT) as the deposition process [7], and was adopted for the production of an AA2319 aluminium frame for aerospace applications.

2.1. Cradle-to-gate life cycle assessment

A cradle-to-gate Life Cycle Assessment (LCA) was performed for each of the considered components. The functional unit was a single produced part. The boundaries of the study included the raw material production, the pre-manufacturing phases for the production of the incoming feedstock materials and all the manufacturing steps. Each step required energy and resources (e.g., the consumables, such as the tooling, cutting fluid or shielding gas), and produced emissions and waste streams. The methodology recently proposed in [8] (recalled in Fig. 2) was adapted to the case studies. The machining approach (i.e., a milling process) was the only one here assumed for comparison purposes, since the part dimensions were not suitable for production by means of powder-bed AM

* Corresponding author.
E-mail address: luca.settineri@polito.it (L. Settineri).

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Table 1
The components assumed as case studies.

Component	Material	Standard manufacturing process
Aerospace frame	AA2319	Machined from billet
Cantilever beam	ER70s-6	Machined from billet
Aerospace bracket	Ti-6Al-4V	Machined from forging

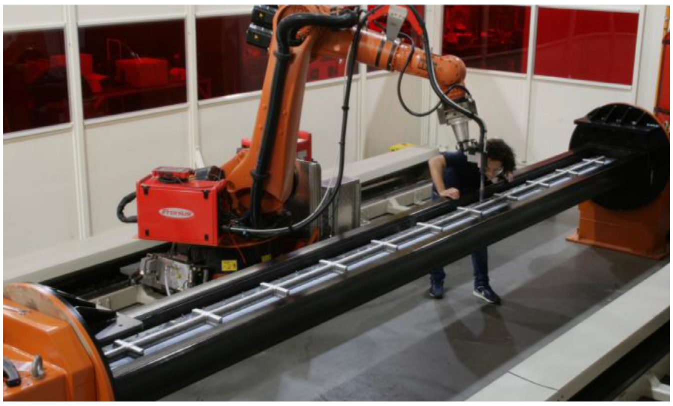

Fig. 1. Overall view of the WAAM system (Cranfield University).

technologies (e.g., EBM or SLM). All the life cycle phases that can be assumed to be identical for both approaches and the transportation-related impacts on a per-part basis were overlooked for the present research purposes.

WAAM was used to melt the metal wire (the weight of which was labelled as m_{wire} in Fig. 2) in order to create the additively manufactured part. The deposition was carried out on a massive substrate, weighing m_{sub}, which was a simple-shaped portion of the final component (i.e., a plate or a billet) previously manufactured through other, usually faster, processes (such as hot rolling, followed by plasma or waterjet cutting, followed by hole drilling to clamp the substrate onto the baseplate of the WAAM system). The WAAM-ed part underwent a case-specific finish machining operation (thereby removing a machining allowance weighing m_a), which was necessary to achieve a satisfactory quality of the surface. On the other hand, the machining-based approach allowed the final component to be obtained by removing the excess material from a workpiece (weighing m_{wp}) in the form of chips (weighing m_c). The raw material production and the pre-manufacturing phases (i.e., forming and wire drawing) were included, together with their material waste streams, for both

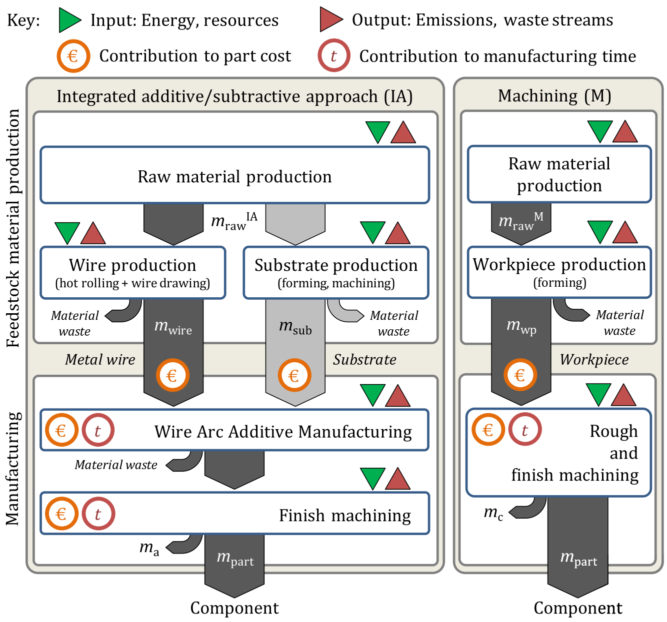

Fig. 2. Unit processes and main qualitative flows of the additive/subtractive and pure subtractive manufacturing approaches.

of the manufacturing approaches. The differences in the amount of raw material (m_{raw}^{IA} or m_{raw}^{M}) needed to produce the same part (weighing m_{part}) reflected the material usage efficiency of each approach.

2.2. Comparative multi-criteria decision-analysis mapping

The deterministic Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Multi-Criteria Decision Analysis (MCDA) method was combined with a weighting technique, based on the ordinal combinatorial ranking of seven criteria automatically set according to the four distribution laws (i.e., 'uniform', 'halving', 'quadratic', 'first two') shown in Fig. 3, and grouped into the four categories (i.e., cost, time, quality and environmental sustainability) as indicated in Table 2. Such an approach generates high-resolution maps of the decision-making space [9]. The cradle-to-gate LCA study in Section 2.1 provided the economic and environmental sustainability indicators as well as the manufacturing time estimates. Quantities measured during mechanical tests on parts produced by WAAM provided a proxy for the in-use material performance, which was loosely labelled with the more compact 'quality' category name. Each TOPSIS analysis (characterised by one weight distribution) ranked the two competing alternatives (i.e., the manufacturing approaches) with a final score *s*- which was higher for the better alternative.

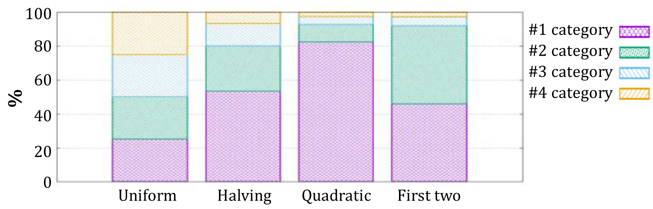

Fig. 3. Distribution laws applied to the criteria weights in the TOPSIS decision-making algorithm used to map the decision space [9].

Table 2
Criteria categorisation for the decision mapping study.

Criterion	Category
Cumulative Energy Demand	Environmental Sustainability (e)
CO_2 emissions	Environmental Sustainability (e)
Manufacturing time	Time (t)
Product cost	Cost (c)
Ultimate tensile strength	Quality (q)
Yield strength	Quality (q)
Elongation at break	Quality (q)

3. Life cycle inventory

The WAAM unit-process values, including the related costs, were obtained from the Welding Engineering and Laser Processing Centre at Cranfield University. The data regarding the raw material production, the pre-manufacturing phases and the machining unit processes were extracted from the CES Selector database [10].

3.1. Material production and pre-manufacturing

The main material flows for both of the manufacturing approaches were experimentally quantified and are summarised in Table 3. In order to account for any unavoidable waste that occurred during each step, the ratio between the mass of the material entering the unit process and the one remaining in the output product was set to 1.14 for wire drawing and 1.05 for hot shape rolling, considering the average values of the material utilisation fraction given in [10]. Permanent material losses of WAAM, which can be traced back to (*i*) in-process material vaporisation, (*ii*) small droplets of molten material that are dispersed outside the deposition area when welding, and (*iii*) wire scraps, were estimated on the basis of laboratory experience. An input/output material ratio of 1.02, corresponding to a material-usage efficiency of approximately 98%, was assumed for WAAM. The range of values used to compute the energy demand and carbon footprint of different unit processes is listed in Table 4

Table 3
Main material flows (labelled according to Fig. 2), in kg.

Component	m_{part}	m_{sub}	m_{wire}	m_a	m_{wp}	m_c
Aluminium frame	17	48	33	63	399	382
Steel beam	188	400	143	352	1396	1208
Titanium bracket	7.8	7.0	12.2	11.2	62.4	54.6

Table 4
Specific energy demand of each unit process, in MJ/kg [10].

Unit process	Aluminium	Steel	Titanium
Raw material production	127.1 ± 5%	18.5 ± 5%	556.2 ± 5%
Hot rolling / Forging	6.6 ± 5%	20.7 ± 14%	14.7 ± 5%
Wire drawing	47.3 ± 5%	15.6 ± 14%	108.5 ± 5%
Rough machining	1.4 ± 5%	0.8 ± 5%	2.7 ± 5%
Finish machining	9.9 ± 5%	3.6 ± 5%	22.1 ± 5%

Table 5
Carbon footprint of each unit process, in $kgCO_2/kg$ [10].

Unit process	Aluminium	Steel	Titanium
Raw material production	8.41 ± 5%	1.63 ± 5%	32.98 ± 5%
Hot rolling / Forging	0.49 ± 5%	1.55 ± 14%	1.11 ± 5%
Wire drawing	3.55 ± 5%	1.17 ± 14%	8.13 ± 5%
Rough machining	0.11 ± 5%	0.06 ± 5%	0.20 ± 5%
Finish machining	0.74 ± 5%	0.27 ± 5%	1.66 ± 5%

Table 6
Purchase cost of the incoming feedstock materials, in €/kg.

Feedstock	Aluminium	Steel	Titanium
Wire material	81.9 ± 15%	1.2 ± 15%	117.0 ± 15%
Bulk material	41.0 ± 15%	0.5 ± 15%	46.8 ± 15%

and Table 5, respectively. The impact of the raw material production phase was estimated by accounting for the benefits due to the upstream flow of recycled material in the current supply, as proposed by Hammond and Jones [11]. An average recycled content of 43% was assumed for aluminium, 42% for steel and 22% for titanium [10]. The purchase cost of the incoming feedstock materials was obtained from a market analysis, and *a* ± 15% range of variation was considered (Table 6).

3.2. WAAM unit process

The electric energy requirements of the WAAM system and its main auxiliary equipment (e.g., the chiller for cooling the power source) were monitored during the productive and non-productive times (i.e., from the start-up to the shut-down), together with the consumption of the shielding gas (Argon). Average deposition rates of (*i*) 2.40 kg/h for aluminium, (*ii*) 0.94 kg/h for steel and (*iii*) 0.66 kg/h for titanium were applied. The specific electric energy consumption of the deposition phase (i.e., regarding only the arc-on time) was quantified as (*i*) 6.3 MJ/kg for aluminium, (*ii*) 23.7 MJ/kg for steel and (*iii*) 33.4 MJ/kg for titanium. These results are consistent with the available literature sources [12, and references therein]. The energy consumption of motion provision systems appeared to be negligible. A conversion coefficient of 0.38 was assumed to correct the electric energy demand back to the primary energy, and the carbon emission signature of the electric grid was set at 0.447 $kgCO_2/kWh$ [8]. The cost of each as-deposited component (i.e., before the finish machining operations) was quantified using a standard procedure developed at Cranfield University, which accounts for (*i*) the purchasing costs of all the consumables, (*ii*) the production costs (including setup, work-frame calibration, substrate preparation, part building), (*iii*) the labour costs, and (*iv*) the delivery costs, overheads and facility charges. As far as the tooling for WAAM is concerned, the cost of the clamping system (usually made of steel) is related to the dimensions of the substrate/part being produced. This cost could range from € 300–400 to more than € 5000 (as for the clamping system for the 5 m long beam). However, the contribution of tooling to the assessment can be overlooked on a per-part basis when a series production is assumed (as in this research).

3.3. Machining unit processes

The impact of the machining unit processes was estimated for both the finishing operations on the WAAM-ed part and the pure subtractive manufacturing approach (Fig. 2). Milling tools that would be suitable to machine each feature of the components and the recommended process parameters were identified from cutting tool supplier catalogues. The ranges of the Material Removal Rate (MRR) that had to be applied are listed in Table 7. The unit-process times were estimated from the MRR ranges, including an average non-productive time of 1 h. The specific energy demand and the carbon footprint which were used to quantify the impact of rough and finish machining, as a function of the workpiece material, are listed in Table 4 and Table 5, respectively. This choice was motivated by the need to maintain the consistency of the database with the assumptions concerning the feedstock material production phases. It is worth noting that, when the MRRs listed in Table 7 are applied to the Specific Energy Consumption (SEC) models proposed by Kara and Li [13], and then later on by other authors [14], proportionate (even though slightly) higher values are obtained. Each machine tool is expected to be characterised by a certain SEC versus MRR curve, with only a slight impact from the cutting process. Since the dimensions of the parts in each case study were rather different, and required different equipment, the here estimated ranges were assumed as representative of an industrial production. As far as the milling costs are concerned, the same cost items listed in Section 3.2 for the WAAM unit process were considered, and the methodology detailed in [8] was applied to identify the (wide) ranges of variation in the input data. In particular, the hypothesised indirect cost rate was from 12.7 €/h to 23.7 €/h, and the labour charge rate was 18.4 €/h to 24.9 €/h.

Table 7
Material Removal Rate (MRR), in kg/h.

Milling operation	Aluminium	Steel	Titanium
Roughing	18.7–26.3	9.4–13.2	1.6–2.2
Finishing	0.9–1.3	1.3–1.9	0.1–0.2

4. Results

The main results, in terms of Cumulative Energy Demand (CED), manufacturing time and product costs, are plotted in Fig. 4 for all the case studies. The CO_2 emission trends were similar to those of the CED. The variability in the input values resulted in a variability of the results, as represented by the error bars. The CED is dominated by the feedstock material production. The higher the material-usage efficiency of the

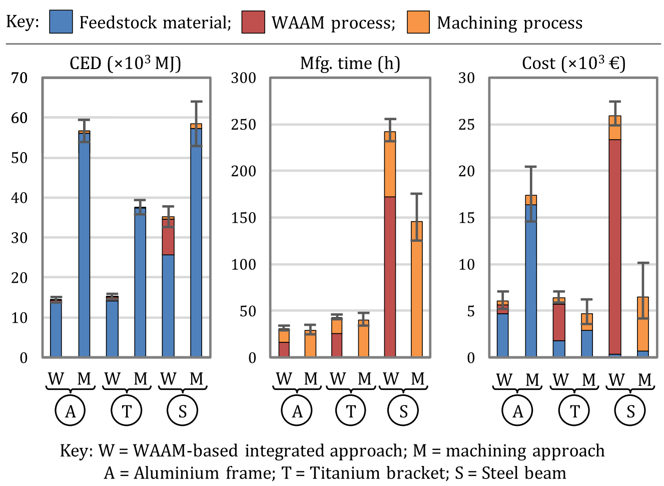

Fig. 4. Cradle-to-grate Life Cycle Assessment results.

manufacturing approach is (Table 3), the lower the impact [8,14]. The time necessary to manufacture the titanium bracket and the aluminium frame is basically comparable (as the WAAM-ed parts require a non-negligible finish machining operation), while it is higher for the WAAM-ed steel beam. The product costs were affected by both the cost for purchasing the necessary amount of feedstock materials and the manufacturing time. As for the mechanical characterisation (the results of which have here been omitted for confidentiality reasons), the WAAM samples showed slightly lower ultimate tensile strength and yield strength values (minus 3–8%) and, in some cases, higher elongation at break values than the expected values for the parental materials.

5. Multi-criteria analysis and discussion

The combination of the categorised criteria showed that a WAAM-produced aluminium alloy frame could be a strong contender for conventional processes. This clearly emerges when the criterion categories are equally important (Fig. 5), or when emphasis is on the environmental sustainability performance of the process (right-hand part in Fig. 6 for all the distribution laws). The ranking of the categories (dictating their importance for the decision maker) is indicated on the horizontal axes in Fig. 6 by a sequence of each category initial (i.e., 'c' for cost, 't' for time, 'q' for quality and 'e' for environmental sustainability). The only cases in which conventional processes would be preferred to produce the aluminium alloy frame require the predominant importance of a combination of time and cost. It is more convenient to manufacture the steel infrastructural beam by means of conventional methods, and the area where WAAM retains a clear advantage is reduced to cases in which environmental sustainability is the single most important category (i.e., a 'quadratic' weight distribution law starting with 'e' in Fig. 6). However, it is interesting to note how the high-resolution mapping exposes some isolated corner cases when WAAM would still be preferred ('tqce' and 'qtce' of the 'first two' map at the bottom of Fig. 6). Finally, the titanium bracket clearly sits in the middle of the first two cases and shows a mixture of their characteristics. Overall, Figs. 5 and 6 show that the process selection of real-world cases (like the ones presented in this work) is complex, and a detailed map appears to be beneficial to consider the relevant trade-offs.

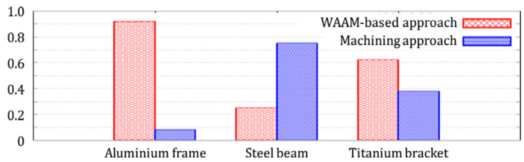

Fig. 5. Uniform weight distribution scores (s^-).

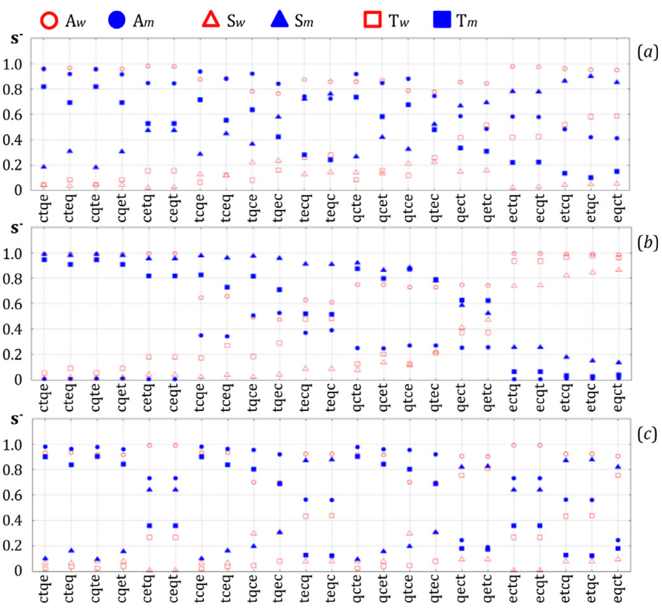

Fig. 6. Mapping of the results corresponding to the 'halving' (a), 'quadratic' (b) and 'first two' (c) weight distributions.

6. Conclusions

The paper has focused on a comparison of WAAM-based additive/subtractive manufacturing approaches and machining. Medium-to-large components were assumed as case studies. A methodology that allows the cumulative energy demand and CO_2 emissions to be quantified was applied. The manufacturing time, product cost and mechanical performance of the materials were also considered for comparison purposes. The results highlight a remarkable reduction in resource/energy requirements and CO_2 emissions when the WAAM-based approach is used. Conversely, the time and costs depend on the component and the material being used. It is worth underlining that the part geometry can be expected to affect the outcome of the proposed comparative study, as already shown in [8], when the solid-to-cavity ratio is varied. The TOPSIS Multi-Criteria Decision Analysis method was coupled with a combinatorial weighting technique to generate high-resolution maps of the results within the decision-making space. Overall, even though the presented results are only valid for the considered assumptions, the methodology can be proposed as a tool to support process selection with environmental and economic objectives.

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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