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Metal additively versus conventionally manufactured structures – An environmental life cycle assessment

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Abstract

The use of wire arc additive manufacturing (WAAM) in conjunction with topology optimisation enables the production of structural components with significantly higher strength-to-weight ratios than conventional structural components. However, owing to the additional production stages involved in WAAM (*e.g.* arc welding), a common question arises regarding the environmental impacts of using WAAM to produce structural components relative to conventional fabrication techniques (*e.g.* hot-rolling.) A cradle-to-gate life cycle assessment is conducted herein to compare the environmental performance of a conventional hot-rolled I-section steel beam with that of a topologically optimised WAAM beam, the latter having 53% lower mass than the former. With regards to climate change, it is demonstrated that, for a typical deposition rate of 2 kg/h, WAAM can lead to lower CO_2-eq. emissions than conventional hot-rolling if topology optimisation can offer mass reductions of at least ~50%. The contribution of the individual processes in WAAM production is analysed, demonstrating that the use of shielding gas is the greatest contributor to the climate change impact of WAAM production.

Keywords

Additive manufacturing, Environmental performance, Life cycle assessment, Steel structures, Sustainability, Topology optimisation, Wire arc additive manufacturing

1 Introduction

Wire arc additive manufacturing (WAAM) is a metal 3D printing technique that utilises a robotic arm in conjunction with off-the-shelf arc welding equipment, as shown in Figure 1, to print components in a layer-upon-layer fashion [1]. The use of WAAM in conjunction with topology optimisation has opened up new opportunities for the production of structurally optimised components with higher load-carrying capacity-to-weight ratios than conventionally produced components [2]. For instance, Ye *et al*. [3] developed an end-to-end framework that exploits the geometric freedom offered by WAAM to generate 2 m long topologically optimised trusses, such as the cantilever shown in Figure 2, comprising circular tubular cross-sections of variable thickness and diameter.

A common question arises regarding the environmental sustainability of WAAM production in comparison with conventional fabrication techniques, such as hot-rolling, since WAAM involves the use of additional production stages, such as wire drawing and arc welding. Hence, considering both the additional energy inputs required in WAAM and the significant material savings that it can offer when combined with topology optimisation, the present paper answers the following questions:

(1) What are the environmental impacts of using WAAM for construction applications?

(2) What is the scale of material savings that must be attained for WAAM to have lower environmental impacts than hot-rolling?

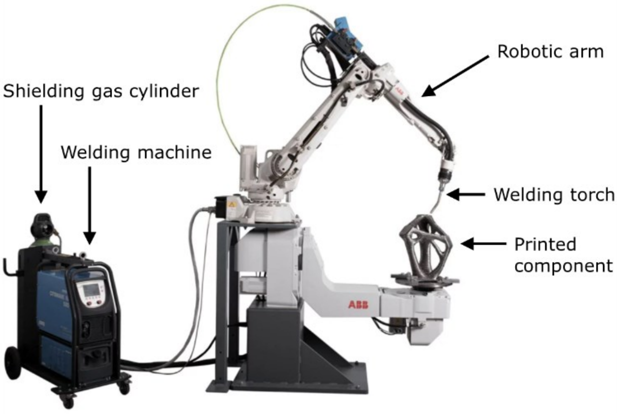

Figure 1 Principal components of a WAAM system [13].

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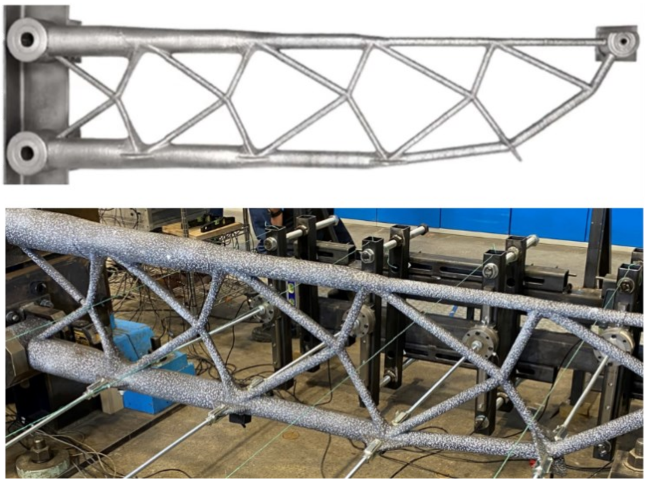


Figure 2 Topologically optimised WAAM cantilever undergoing structural testing at Imperial College London.

For this purpose, the present work conducts a life cycle assessment to compare the environmental performance of WAAM structural members with that of conventional hot-rolled members. Specifically, the environmental impacts of producing (i) a topologically optimised WAAM beam and (ii) a hot-rolled I-section beam are investigated. The two beams have the same load-carrying capacity and span, however, owing to its optimised geometry, the WAAM beam is 53% lighter than the I-section beam.

Only a handful of investigations, including [4–10], have examined the environmental impacts of WAAM. Out of these, the only work that has considered the impacts of WAAM for use in construction applications specifically is the study by Priarone *et al*. [6]. Furthermore, while the aforementioned studies have used either an area- or a mass-based functional unit, this work also considers the function and load-carrying capacity of the structural component by normalising the embodied carbon in the modelled beams with respect to their load-carrying capacity for a given span [11].

In the subsequent sections, following the description of the adopted methodology, the key results of the present study are presented and conclusions are drawn.

2 Methodology

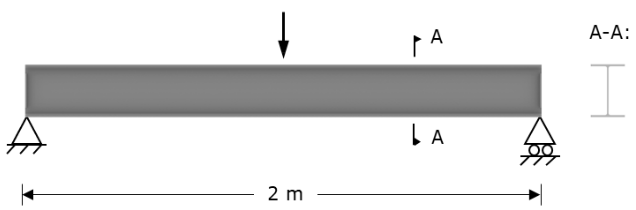
2.1 Functional unit

The functional unit is a 2 m long simply-supported steel beam with a target load of P = 172 kN applied at midspan, as shown in Figure 3. It is assumed that the beam is fully restrained laterally against lateral torsional buckling. This configuration was chosen as the focus of the present study owing to its ubiquitous nature and its general applicability across the construction industry.

The conventional hot-rolled steel beam is a UB 203×133×25 prismatic I-section beam [12], as shown in Figure 3(a). The WAAM beam is shown in Figure 3(b); its geometry was generated by Ye *et al*. [3] using a numerical layout and geometry optimisation technique considering practical and manufacturing constraints. The WAAM beams (see Figures 2 and 3(b)) have been produced by MX3D [13] as specimens for an experimental programme conducted by the Steel Structures Group at Imperial College London.

The I-section beam and WAAM beam have the same bending capacity but different masses; the I-section beam has a mass of 50.2 kg, while the WAAM beam, owing to the topology optimisation process, has a mass of 23.6 kg [3]. Thus, the mass ratio between the I-section beam and the WAAM beam is 2.1:1.

(a) I-section beam



(b) WAAM beam

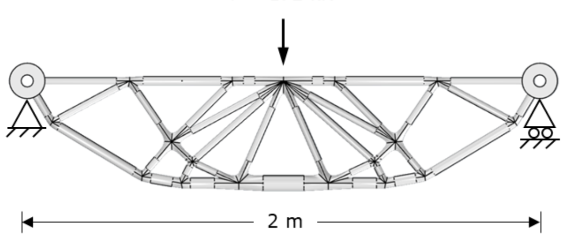


Figure 3 Functional unit; (a) hot-rolled I-section beam and (b) topologically optimised WAAM beam [3].

2.2 Modelling approach and inventory analysis

A cradle-to-gate analysis was conducted herein – *i.e.* the system boundaries included processes from steel production to the fabrication of the steel beams, as shown in Figure 4, and excluded subsequent processes, such as the transportation of the beams from the factory, their maintenance and end-of-life management. The OpenLCA software [14] was used for the analysis.

The steel production, hot-rolling, wire drawing and arc welding processes were modelled based on ecoinvent database v3.4 [15]; the country/region corresponding to each dataset is indicated below in brackets. The ecoinvent process 'market for steel, unalloyed' was used to model carbon steel (Europe) with a similar chemical composition to the commonly used S355 steel grade. Hot-rolling was modelled using the 'hot-rolling, steel' process (Europe). The finishing processes (Europe, alkyd paint; UK Electricity), namely sandblasting and protective painting, were modelled using the 'fine machining' process, based on data from [16], and the ecoinvent process 'solvent-borne alkyd paint', respectively.

Regarding the WAAM process, the production of the welding wire, which is the raw material, was modelled using the 'wire drawing steel' ecoinvent process (Europe), assuming the drawing of 1.0 mm diameter wire from steel rods with diameters 5.5 mm to 16 mm. Arc welding (UK electricity) was modelled manually assuming a deposition rate of 2 kg/h, which is at the upper end of the range of deposition rates used for the fabrication of the MX3D

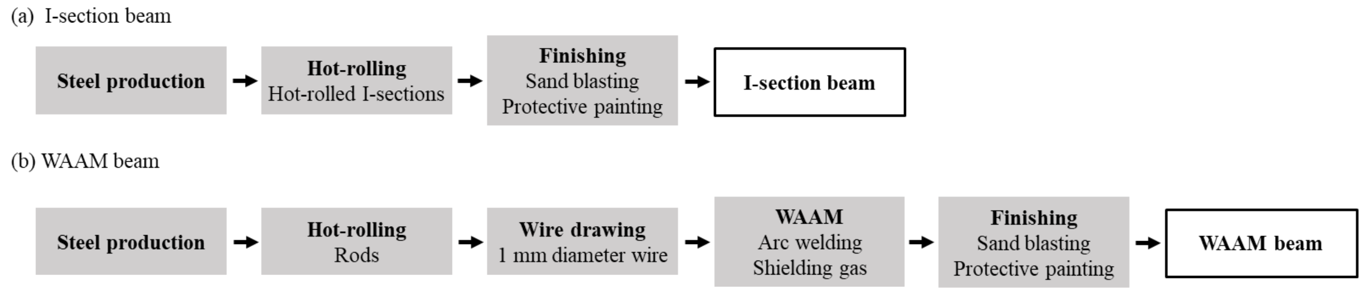


Figure 4 Unit processes involved in the production of the steel beams; reference flows are represented by the black arrows.

Bridge [13,17]. The total energy consumption of the WAAM process was taken as 2.46 kWh per kg of printed material, comprising 1.97 kWh for the arc welding process, based on the work of Joseph *et al*. [18], and 0.22 kWh and 0.27 kWh for the robot movement and ventilation, respectively, both based on the work by Bekker and Verlinden [9]. To protect the weld from atmospheric oxygen and moisture, shielding gas is used in arc welding. In the case of WAAM carbon steel, an 82% Argon and 18% CO_2 gas mixture is typically used [19]. Hence, shielding gas production (Global, argon; Europe, carbon monoxide) was modelled using the ‘market for carbon dioxide, liquid’ and ‘market for argon, liquid’ ecoinvent processes. A typical gas flow rate of 12 L/min corresponded to 0.517 kg of Argon and 0.114 kg of CO_2 per kg of printed material.

The material utilisation fractions utilised herein are listed in Table 1. Accounting for any material waste and losses occurring in each unit process, the material utilisation fractions result in an input mass of 1.04 kg per kilogram of produced I-section beam; this implies that 52.2 kg of steel are required to produce the 50.2 kg I-section beam. In the case of the WAAM beam, the input mass is 1.18 kg per kilogram of product, with the greatest contributor being the wire drawing process; hence, 27.9 kg of steel are required to produce the 23.6 kg WAAM beam.

3 Results

For the life cycle impact assessment, the ReCiPe 2016 method at midpoint level (following a ‘hierarchist’ interpretation) and economic allocation were used. The overall results, corresponding to eighteen midpoint indicators, are given in Table 2. In the case of the chosen functional unit, *i.e.* for a mass ratio between the I-section beam and the WAAM beam of 2.1, it is observed that the I-section beam has higher environmental impacts than the WAAM beam in eight categories, including climate change and metal depletion. In the case of climate change, the WAAM beam has slightly lower impact (7%) than the I-section beam. In the case of metal depletion, the I-section beam is 88% more impactful than the WAAM beam owing to the high (53%) mass reduction achieved by means of topology optimisation in the case of the latter. These results are analysed further in the subsequent sub-sections.

Table 3 Contribution of unit processes to climate change impact.

Unit Process	I-section beam (kg CO_2-eq.)	WAAM beam (kg CO_2-eq.)
Steel production	99.7	44.3
Hot-rolling	6.96	3.10
Wire drawing	–	1.94
WAAM	–	54.8
Sand blasting	0.248	0.117
Protective painting	10.6	4.96
Total impact	117	109

3.1 Contribution of unit processes

The contribution of the unit processes to the overall impacts of hot-rolling and WAAM production on climate change are listed in Table 3. As expected, steel production has the highest contribution (85%) to the total impact of hot-rolling. Thus, it can be concluded that reductions in the overall mass of the beam would lead to significant environmental benefits. In the case of the WAAM beam, the contribution of steel production to the total impact of WAAM production is 41%; similar contributions, *i.e.* 45% and 35%, respectively, have been reported by Kokare *et al*. [8] and Priarone *et al*. [6]. Owing to the 53% material savings obtained by means of topology optimisation in the WAAM beam analysed here and shown in Figure 3(b), the impact of steel production in the case of the WAAM beam is 56% lower than that of the I-section beam. However, the contribution of the WAAM process offsets the entire (99%) reduction in the impact of steel production that was achieved by topologically optimising the beam.

The overall impact of the WAAM process is analysed further in Figure 5, where the impact of its contributing elements – *i.e.* the electricity for arc welding, robot movement and ventilation, the energy for the production of the shielding gas and the energy for the production of the electronics of the WAAM system – is shown. The significant contribution of the shielding gas, primarily argon, is noteworthy; for instance, in the case of climate change impact, Argon accounts for 60% of the overall impact of the WAAM process.

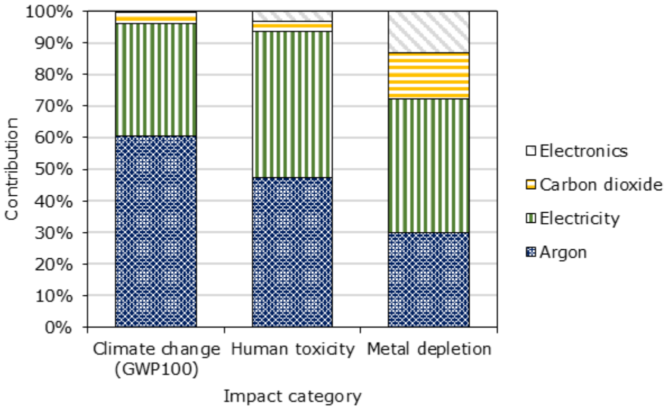


Figure 5 Contributing elements to the impact of the WAAM process.

Table 1 Material utilisation fractions.

Unit process	Material utilisation fraction (–)	Mass before process (kg)
For 1 kg I-section beam		
Steel production[1]	1.00	1.04
Hot-rolling[2]	0.96	1.04
Sand blasting[3]	0.99	1.01
Protective painting[4]	1.00	1.00
For 1 kg WAAM beam		
Steel production[1]	1.00	1.18
Hot-rolling[2]	0.96	1.18
Wire drawing[5]	0.90	1.13
Welding[6]	0.99	1.02
Sand blasting[3]	0.99	1.01
Protective painting[4]	1.00	1.00

[1] Assuming negligible material losses during continuous casting.

[2] Taken as the average of the values reported in [15,16,20].

[3] Accounting for the removal of some material from the surface.

[4] No material removed during painting.

[5] Material loses owing to descaling, cutting scrap and dust; based on [15–16].

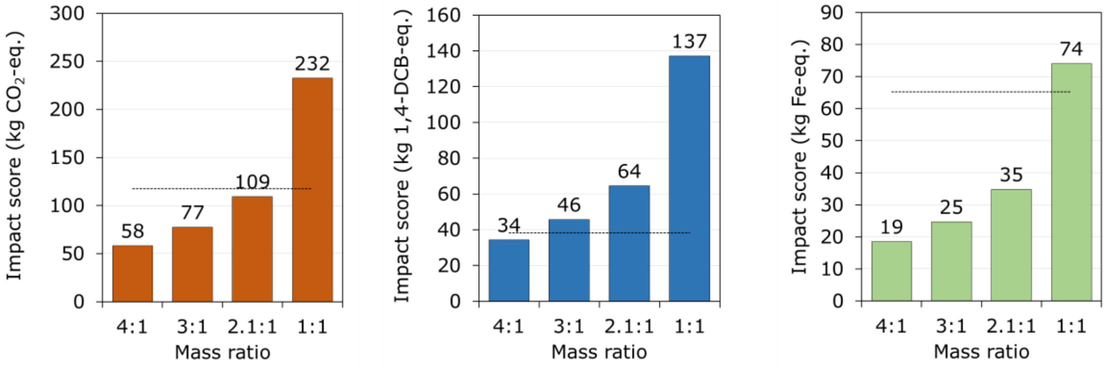
[6] Accounting for welding spatter and wire cuts [9].

Table 2 ReCiPe 2016 midpoint impact results [a].

Impact category	Unit	I-beam	WAAM beam (mass ratio)		
			(1:1)	(2.1:1)	(3:1)
Agricultural land occupation	m^{2}a	0.197	**0.417**	0.196	0.139
Climate change (GWP100)[b]	kg CO_2-eq.	117	**232**	109	77.4
Fossil depletion	kg oil-eq.	31.3	**66.9**	**31.4**	22.3
Freshwater ecotoxicity	kg 1,4-DCB-eq.	1.28	**3.54**	**1.66**	1.18
Freshwater eutrophication	kg P-eq.	0.0537	**0.127**	**0.0598**	0.0424
Human toxicity	kg 1,4-DCB-eq.	38.3	**137**	**64.5**	**45.8**
Ionising radiation	kBq U_{235}-eq.	6.74	**54.2**	**25.5**	**18.0**
Marine ecotoxicity	kg 1,4-DCB-eq.	1.23	**4.39**	**2.07**	**1.46**
Marine eutrophication	kg N-eq.	0.132	**0.487**	**0.229**	**0.162**
Metal depletion	kg Fe-eq.	65.3	**74.0**	34.8	24.7
Natural land transformation	m^2	0.0371	**0.0423**	0.0199	0.0141
Ozone depletion	kg CFC-11-eq.	7.57×10^{-6}	**1.82×10^{-5}**	**8.45×10^{-6}**	5.99×10^{-6}
Particulate matter	kg PM_{10}-eq.	0.433	**0.771**	0.362	0.257
Photochemical oxidant	kg NMVOC	0.579	**0.857**	0.403	0.286
Terrestrial acidification	kg SO_2-eq.	0.516	**0.921**	0.433	0.307
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	0.0781	**0.215**	**0.101**	0.0715
Urban land occupation	m^{2}a	1.09	**1.58**	0.741	0.525
Water depletion	m^3	0.367	**1.05**	**0.493**	0.350

[a] Values in **bold** show the highest impact between the I-section beam and the WAAM beam.

[b] Reported using global warming potential over a 100-year horizon (GWP100).



(a) Climate change (GWP100) (b) Human toxicity (c) Metal depletion

Figure 6 Influence of I-section to WAAM beam mass ratio on the environmental impacts of the WAAM beam relative to the I-section beam. The horizontal dashed line represents the value corresponding to the I-section beam.

The impact of the shielding gas is driven primarily by the high electricity consumption involved in its own production. Thus, the use of renewable sources of energy could potentially reduce the impacts of both arc welding and shielding gas production. Therefore, it is expected that the climate change impact of WAAM will reduce substantially in the future, in line with decarbonisation of the energy system. Furthermore, the impact of the shielding gas can be reduced significantly by using higher deposition rates [9] – for instance, doubling the deposition rate would halve the printing time and therefore halve the volume of shielding gas required per kg of printed material.

3.2 Influence of mass reductions

The achieved mass reductions can vary significantly depending on the design parameters, such as the end support conditions and loading conditions [3]. In practice, even greater mass reductions than the one considered in previous sections can be achieved. Hence, to investigate the effects of the degree of mass reduction on the environmental performance of the WAAM beam, four additional analyses have been conducted. Hypothetically, the mass of the WAAM beam was chosen as 12.6 kg, 16.7 kg and 50.2 kg, corresponding to mass ratios (mass of I-section beam over mass of WAAM beam) of 4:1, 3:1 and 1:1, respectively, and thus mass reductions of 75%, 67% and 0%, respectively.

The results from the additional analyses corresponding to the impact categories of climate change, human toxicity and metal depletion are shown in Figure 6. As expected, the higher the degree of achieved mass reductions, the lower the environmental impacts of the WAAM beam (bar values) relative to the impacts of the I-section beam (horizontal dashed line.) Using linear interpolation between the results of the modelled cases, the break-even points of 2:1, 3.7:1 and 1.1:1 were identified for the climate change, human toxicity and metal depletion categories, respectively; at reduced WAAM beam masses, *i.e.* at higher mass ratios, WAAM leads to relatively lower environmental impacts than hot-rolling. Thus, for instance, in the case of climate change, WAAM can result in lower CO$_2$-eq. emissions than hot-rolling when at least 50% materials savings can be achieved using, for instance, topology optimisation. In practice, such mass reductions are readily attainable.

4 Conclusions

The aim of the present paper was to compare the environmental performance of wire arc additively manufactured (WAAM) structural components with that of conventional hot-rolled steel components. For this purpose, using life cycle assessment, the environmental impacts of producing a topologically optimised WAAM beam were compared to those of a hot-rolled I-section beam. The functional unit was a 2 m long steel beam with a target load of 172 kN applied vertically downwards at midspan. Owing to the significant mass savings (53%) obtained using topology optimisation, the WAAM beam had capacity-to-mass ratio that was 2.1 times that of the I-section beam.

The results showed that, for a typical deposition rate of 2 kg/h, the WAAM beam had slightly lower (7%) impact to climate change than the I-section beam. As expected, steel production was the biggest contributor (85%) to hot-rolling production. In the case of the WAAM beam, for an the biggest contributor (50%) was the WAAM process, which has been shown to offset almost the entire benefits offered by the material savings (in the case when the mass ratio between the I-section beam and the WAAM beam was 2.1:1). Furthermore, it has been concluded that the use of shielding gas (primarily argon) contributes even more than the electricity used in the WAAM process.

A sensitivity analysis was conducted to investigate the influence of the mass reductions; for this purpose, additional analyses were conducted assuming mass ratios between the I-section beam and the WAAM beam of 4:1, 3:1 and 1:1. The break-even points of 2:1, 3.7:1 and 1.1:1 were identified for the climate change, human toxicity and metal depletion impact categories, respectively; when material savings corresponding to higher mass ratios than the above can be achieved using, for instance, topology optimisation, WAAM leads to relatively lower impacts in the aforementioned categories than hot-rolling. For instance, for a typical deposition rate of 2 kg/h, WAAM can lead to a lower climate change impact than hot-rolling, provided that at least 50% mass savings can be obtained by means of topology optimisation.

Further work to investigate the influence of the deposition rate, which can reduce the contribution of the shielding gas significantly, and the proportion of renewable energy sources used in the electricity mix, which can reduce the impacts of the WAAM process further, has been proposed.

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References

[1] Williams, S.W.; Martina, F.; Addison, A.C.; Ding, J.; Pardal, G.; Colegrove, P. (2016) Wire+Arc additive manufacturing. Mater. Sci. Technol. 32, 641–647.

[2] Gardner, L. (2023) Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook. Structures 47, 2178–2193.

[3] Ye, J.; Kyvelou, P.; Gilardi, F.; Lu, H.; Gilbert, M.; Gardner, L. (2021) An end-to-end framework for the additive manufacture of optimised tubular structures. IEEE Access 9, 165476–165489.

[4] Campatelli, G.; Montevecchi, F.; Venturini, G.; Ingarao, G.; Priarone, P.C. (2019) Integrated WAAM-subtractive versus pure subtractive manufacturing approaches: an energy efficiency comparison. Int. J. Precis. Eng. Manuf. Technol. 7, 1–11.

[5] Priarone, P.C.; Campatelli, G.; Montevecchi, F.; Ventrurini, G.; Settineri, L. (2019) A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining. CIRP Ann. 68, 37–40.

[6] Priarone, P.C.; Pagone, E.; Martina, F.; Catalano, A.R.; Settineri, L. (2020) Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing. CIRP Ann. 69, 37–40.

[7] Dias, M.; Pragana, J.P.M.; Ferreira, B.; Ribeiro, I.; Silva, C.M.A. (2022) Economic and environmental potential of wire-arc additive manufacturing. Sustainability 14, 5197.

[8] Kokare, S.; Oliveira, J.P.; Santos, T.G.; Godina, R. (2023) Environmental and economic assessment of a steel wall fabricated by wire-based directed energy deposition. Addit. Manuf. 61, 103316.

[9] Bekker, A.C.M.; Verlinden, J.C. (2018) Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel. J. Clean. Prod. 177, 438–447.

[10] Reis, R.C.; Kokare, S.; Oliveira, J.P.; Matias, J.C.O.; Godina, R. (2023) Life cycle assessment of metal products: A comparison between wire arc additive manufacturing and CNC milling. Adv. Ind. And Manuf. Eng. 6, 100117.

[11] Purnell, P. (2012) Material nature versus structural nurture: the embodied carbon of fundamental structural elements. Environ. Sci. Technol. 46, 454–461.

[12] British Steel (2018) Building Stronger Futures. Sections - Universal Beams (Dimensions and Properties to BS EN 10365:2017). URL. https://britishsteel.co.uk/media/377384/british-steel-universal-beams-datasheet.pdf (accessed 21.02.22).

[13] MX3D (2023) MX3D bridge. URL. https://mx3d.com/industries/infrastructure/mx3d-bridge/ (accessed 19.2.23).

[14] GreenDelta (2020) OpenLCA 1.10 – Comprehensive User Manual.

[15] ecoinvent (2020) Ecoinvent 3.4. URL. https://www.ecoinvent.org/database/older-versions/ecoinvent-34/ecoinvent-34.html (accessed 8.15.21).

[16] Granta Design (2019) Ansys Granta EduPack: Materials Information Management.

[17] Gardner, L.; Kyvelou, P.; Herbert, G.; Buchanan, C. (2020) Testing and initial verification of the world's first metal 3D printed bridge. J. Constr. Steel Res. 172, 106233.

[18] Joseph, A.; Harwig, A.; Farson, D.F.; Richardson, R. (2003) Measurement and calculation of arc power and heat transfer efficiency in pulsed gas metal arc welding. Sci. Technol. Weld. Join. 8 (6), 400–406.

[19] Huang, C.; Kyvelou, P.; Zhang, R.; Britton, T.B.; Gardner, L. (2022) Mechanical testing and microstructural analysis of wire arc additively manufactured steels. Mater. Des. 216, 110544.

[20] Rentz, O.; Jochum, R.; Schultmann, F. (1999) Report on Best Available Techniques (BAT) in the German Ferrous Metals Processing Industry. French-German Institute for Environmental Research, Karlsruhe.