Results in Engineering 27 (2025) 105610

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Research paper

Reduction of the environmental impact of complex-shaped steel joints through topology optimization and large-scale metal 3D printing

Vittoria Laghi [*], Elisabetta Savino [*], Giada Gasparini

Department of Civil, Chemical, Environmental and Materials Engineering (DICAM) - University of Bologna, Viale del Risorgimento, 2 – 40136 Bologna, Italy

A R T I C L E I N F O

Keywords:
DED-Arc
Topology optimization
CNC milling
Life-Cycle Assessment

A B S T R A C T

Metal Additive Manufacturing (or 3D printing) technologies are bringing substantial changes to the entire industrial environment, enabling rapid and cost-effective production of complex components which would be hardly fabricated with conventional technologies. Recent developments in the field of large-scale metal 3D printing increased the potential use for the construction sector, with applications in some pioneering case studies. The present work is intended to assess the potential environmental benefit of the combination of digital technologies such as topology optimization and large-scale metal 3D printing to realize complex-shaped steel joints. The study evaluates the environmental impact of Directed Energy Deposition-Arc (DED-Arc) manufacturing adopted to realize optimized steel joints and compared with the Computer-Numerically Controlled (CNC) milling technique adopted to realize conventional steel joints for gridshell structures. The study is applied to the specific steel joints for the gridshell structure of the British Museum in London. The results demonstrate that topology-optimized joints produced via DED-Arc exhibit superior environmental performances, particularly in terms of reduced carbon footprint and material waste. Additional considerations are made regarding the influence of deposition rate and the use of renewable energy on the environmental impact. The results are also validated through uncertainty analyses. Finally, the combined effect of design optimization and 3D printing technology is investigated in terms of both environmental and economic impact. The study reveals overall a positive impact of the combined use of optimization tools and advanced manufacturing technologies towards greener and more efficient steel structures.

1. Introduction

The iron and steel sector is a significant contributor to global carbon emissions and energy consumption, accounting for over 8% of the world's total energy use. To mitigate this impact, the Iron and Steel Technology Roadmap emphasizes the importance of technological advancements and material efficiency to reduce emissions by 2030. This involves optimizing the design and use of steel structures to minimize material consumption and improve efficiency [1,2].

The adoption of new computational design tools would cut the overall environmental footprint of the steel construction field. Indeed, the use of topology optimization in construction has proven not only to enhance structural efficiency but also to reduce material waste and improve sustainability in construction practices [3,4]. However, the conventional fabrication strategies for the production of steel members hamper the application of these tools to create new shapes, having severe limitations in the geometrical freedom of the fabricated parts. Hence, the application of computational design tools for free-form design is often limited to few explorations in pioneering architectural applications. Additionally, existing methods like cast iron and CNC techniques have high energy consumption and produce significant metal waste [5].

Metal Additive Manufacturing (AM) is a rapidly evolving technology allowing the manufacturing of geometrically complex and high-precision metal components that are not technologically or economically feasible to produce using conventional manufacturing techniques, such as casting and forming [6]. Owing to the reduced production waste, enhanced customization, increased material efficiency and short lead times, metal AM opens up a promising path towards the application of the principles of Circular Economy into the steel sector by (i) increasing the structural efficiency of the fabricated parts thus reducing material waste and (ii) simplifying the resource recapture, hence supporting recycling [7]. Metal 3D printing, or AM, complements topology optimization by enabling the production of complex geometries that

---

* Corresponding authors.
E-mail addresses: vittoria.laghi2@unibo.it (V. Laghi), elisabetta.savino4@unibo.it (E. Savino).

https://doi.org/10.1016/j.rineng.2025.105610
Received 15 April 2025; Received in revised form 27 May 2025; Accepted 2 June 2025

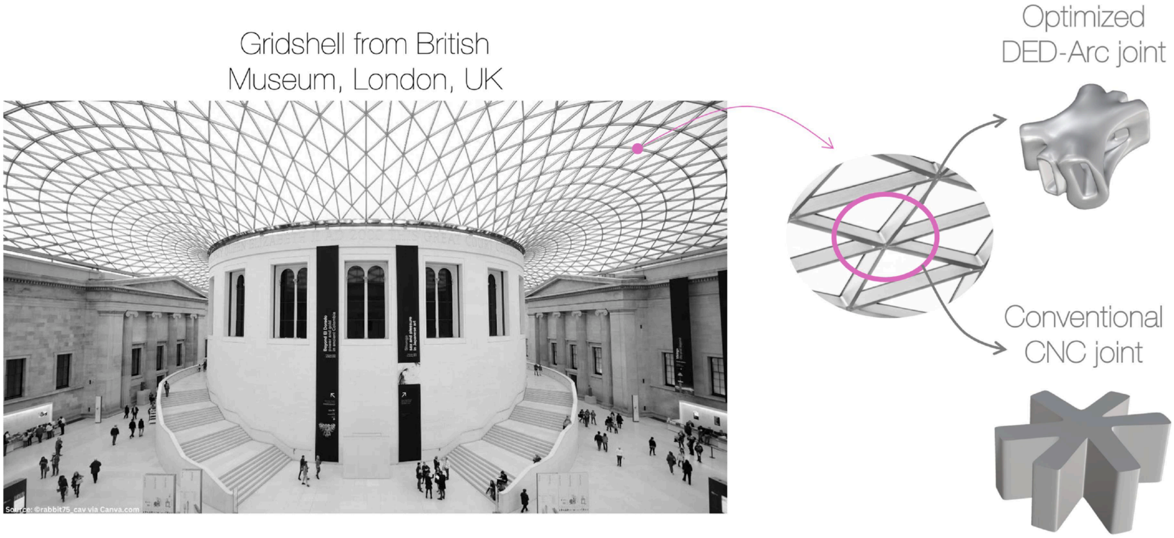


Fig. 1. Case study of British Museum steel gridshell rooftop: conventional CNC-milled joint vs optimized DED-Arc manufactured joint.

conventional manufacturing methods cannot achieve. This synergy allows for the creation of lightweight yet robust structures tailored to specific load conditions and architectural requirements [8,9].

New companies have emerged specializing in the production of large-scale metal 3D printed components. An example is the Dutch company MX3D, which created the world's first 3D-printed steel footbridge using Wire Arc Additive Manufacturing (WAAM) technique [10]. WAAM, also referred to as Directed Energy Deposition-Arc (DED-Arc) technology, is known for its ability to fabricate large-sized components relatively quickly, making it suitable for building large-scale metal structures.

Recent studies focused on the adoption of metal DED-Arc (or WAAM) technologies to produce topology optimized parts. LASIMM and INTEGRADDE projects aimed at proposing WAAM for optimized structural elements [11,12]. MariLight is a UK-funded project focusing on developing lighter marine vessels via topology optimization designs and DED-Arc [13]. Recently, an integrated design and fabrication framework for WAAM-produced parts was proposed to minimize the material use of optimized structural elements while ensuring good structural performances and following the manufacturing constraints proper of the selected fabrication process [14]. Additionally, the research group from Politecnico of Milan investigated different metal AM processes to produce optimized nature-inspired steel nodes for construction [15].

Increasing interest on the environmental impact of novel manufacturing techniques for metal elements has emerged. With specific focus on DED-Arc technologies, limited investigations have been carried out so far. Campatelli et al. [16] compared the total energy demand of an integrated additive-subtractive process (WAAM and milling), demonstrating a lower environmental impact than the purely subtractive process. Priarone et al. [17] compared the cradle-to-gate life cycle assessment (LCA) of three WAAM-produced industrial components, proving that WAAM can lead to substantial reduction in energy use. Dias et al. [18] provided insights on the benefits of using WAAM for its high material efficiency and low waste. Kokare et al. [19] evaluated the cradle-to-gate LCA of a WAAM wall, comparing its performances with a powder-bed fusion (PBF) component and a computer numeric control (CNC) milling, demonstrating that WAAM had higher environmental impact than CNC milling, but could be reduced when more complex geometries were involved in the production. Shah et al. [20] carried out a comparative environmental LCA of WAAM structural members and hot-rolled structural members. The results confirmed that the climate change impact of WAAM production was severely due to the deposition rate and type of energy source adopted. Furthermore, by comparing the environmental effectiveness of WAAM and hot-rolled carbon steel beams it was concluded that WAAM can lead to lower carbon emissions, provided that at least 50 % mass savings is achieved by employing WAAM in conjunction with topology optimization. Hence, in order to create a new generation of green steel structures, novel manufacturing technologies should be employed in conjunction with the adoption of topology optimization algorithms to realize resource-efficient structural elements and systems.

For such reason, this study is focused on the combined application of topology optimization algorithm and large-scale metal AM technology to produce complex-shaped steel joints. In detail, the aim is to assess and compare the environmental impact of two manufacturing techniques suitable for complex-shaped steel joints, i.e. the conventional CNC milling technique and DED-Arc manufacturing. The impact is investigated on the case study of the steel gridshell rooftop of the British Museum by performing a cradle-to-completion Life-Cycle Assessment (LCA) of two different sets of steel joints: (i) the conventional joint adopted for the construction of the gridshell and realized through CNC milling, and (ii) a topologically optimized version to be fabricated with DED-Arc manufacturing [21]. The results will provide insights on the positive impact of digital design and fabrication tools to improve the efficiency of steel construction.

2. Problem formulation

Currently a widely adopted manufacturing technique for complex steel parts in construction is CNC milling, usually simply referred to as CNC manufacturing. This technique has the advantage of fast production at relatively low cost compared to manufacturing through casting. On the other hand, CNC milling is suitable to realize geometries milled from solid parts, thus resulting in high scrap rate.

In this context, metal AM techniques could significantly increase the material utilization, thus reducing the so-called "buy-to-fly" (BTF) ratio usually set at 1.50 for CNC manufacturing [22]. However, widely adopted metal AM technologies such as PBF could result in much higher production time.

DED-Arc manufacturing is a large-scale digital fabrication technique suitable to produce optimized parts, especially shell-like structures (see e.g. the first steel 3D printed footbridge, entirely realized in WAAM [10]). The advantage of this technology lies on the flexibility of the set-up, allowing to realize complex-shaped parts, while keeping a high production rate, up to 10 kg/h [23]. Therefore, DED-Arc manufacturing opens new unexplored ways of fabricating optimized shapes and design

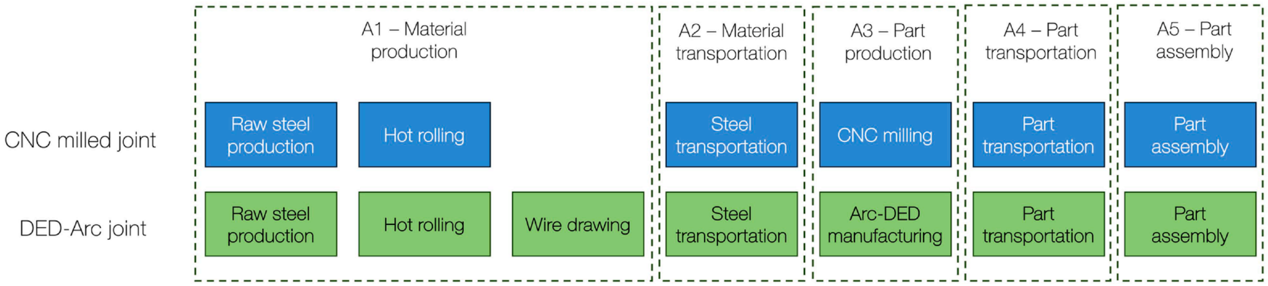


Fig. 2. Processing steps for a steel joint produced with CNC milling and DED-Arc manufacturing.

solutions while significantly reducing the BTF ratio and maximizing the material utilization.

To assess the environmental impact of the fabrication of complex-shaped steel joints, a LCA is carried out for the case study of the grid-shell steel rooftop of the Great Court at the British Museum in London [24]. In detail, the study consists of a comparison in terms of global warming potential (GWP) of the conventional CNC milled joints adopted for the fabrication of the real gridshell with new topology-optimized steel joints adapted for DED-Arc manufacturing (Fig. 1). The optimized joints were conceived on a previous work by Laghi et al. [21] based on the concept of “blended structural optimization”, thus accounting for both the structural requirements and manufacturing constraints of the selected fabrication process. Further details are also provided in Section 3.

The main objective of this work is to compare the environmental impact of the two production techniques adopted to realize complex-shaped steel joints. The analysis is carried on two different functional units. First, the analysis is carried over 1 kg of steel production, to quantify the impact related to the production of the same part, thus not accounting for the premium in flexibility provided by DED-Arc manufacturing to produce more optimized shapes with minimized material use. Then, the analysis is carried on the single joint production, comparing the conventional geometry fabricated with CNC milling with the optimized geometry printed with DED-Arc. For this, additional considerations on the combined benefit of adopting DED-Arc manufacturing with topology optimization are drawn, as presented in Section 6.

To conduct the LCA study, guidelines related to standards ISO 14040 [25], ISO 14044 [26], and ISO 15804 [27] were used. Generally, the LCA evaluates the life cycle of a product through four phases:

- Production: extraction of raw elements and the production of materials and components. Environmental impacts include the extraction of natural resources, energy consumption, and greenhouse gas emissions.
- Construction: final assembly of the product on-site (for example, the construction of a building or the assembly of an industrial plant). It also includes the transportation of components to the site and the use of additional equipment and materials required for the assembly.
- Use: use of the product for its intended purpose. Environmental impacts arise from energy consumption and emissions during operation, as well as maintenance operations impact.
- End of Life: end of the product’s life cycle. Environmental impacts may arise from end-of-life product management, including recycling, disposal, or landfilling.
- Waste Management: management of waste generated during the stages of production, use, and end of life. Environmental impacts may include waste disposal practices, with the potential for soil and water pollution.

The impact of the joints under examination is analyzed through a cradle-to-completion LCA, where the subcategories range from A1 to A5, thus covering only Production and Construction phases, according to ISO 14040 [25]. As previously mentioned, the analysis serves for comparative purpose, and all necessary parameters for conducting the analysis will be defined subsequently. The phases under study are composed by the following stages:

- A1 - Raw material supply: this stage considers the impacts coming from the extraction of raw materials needed for production, including energy consumption, emissions, and generated waste.
- A2 - Plant transportation: this stage evaluates the impacts associated to transport raw materials from their origin to the production facility, including greenhouse gas emissions and fuel consumption.
- A3 - Manufacturing: this stage analyzes the impacts generated during the manufacturing phase, including energy use, emissions, waste production, and others environmental effects related to transform raw materials into the final product.
- A4 - Building site transportation: this stage focuses on the impacts arising from transporting the finished product from the production site to the construction site, considering emissions and energy consumption during transportation.
- A5 - Construction: this stage assesses the impacts related to the actual construction activities, including energy consumption during installation, emissions during construction and waste generated during assembly and installation.

The entire LCA analysis was conducted by simulating the production of the complex-shaped steel joint using conventional CNC milling and DED-Arc manufacturing. Fig. 2 shows the processing steps from raw material to building assembly of a steel part produced via CNC milling and DED-Arc manufacturing. It should be noted that the two processes follow the same steps, except for the additional wire drawing accounted for DED-Arc manufacturing.

3. Structural optimization and analysis on a complex-shaped structural steel joint

One critical aspect of the realization of complex spatial structures is the combination of highly-optimized designs with the common limitations of structural design and construction, from the uncertainties related to loads and supports to the manufacturing constraints. For this, a new structural optimization framework referred to as “blended” optimization was recently proposed [28]. The framework is conceived to integrate computational design, manufacturing constraints and structural performance requirements for WAAM-produced structural steel elements and joints.

The framework was first introduced for structural elements, such as beams [28], then applied to redesign the structural joints of gridshell covering the Great Court of the British Museum [21]. The approach considered both global (whole structure) and local (individual joint) scales. At the global level, the structure was analyzed based on joint-specific considerations. At the local level, a topology optimization algorithm was then used to generate a catalogue of joint designs, which

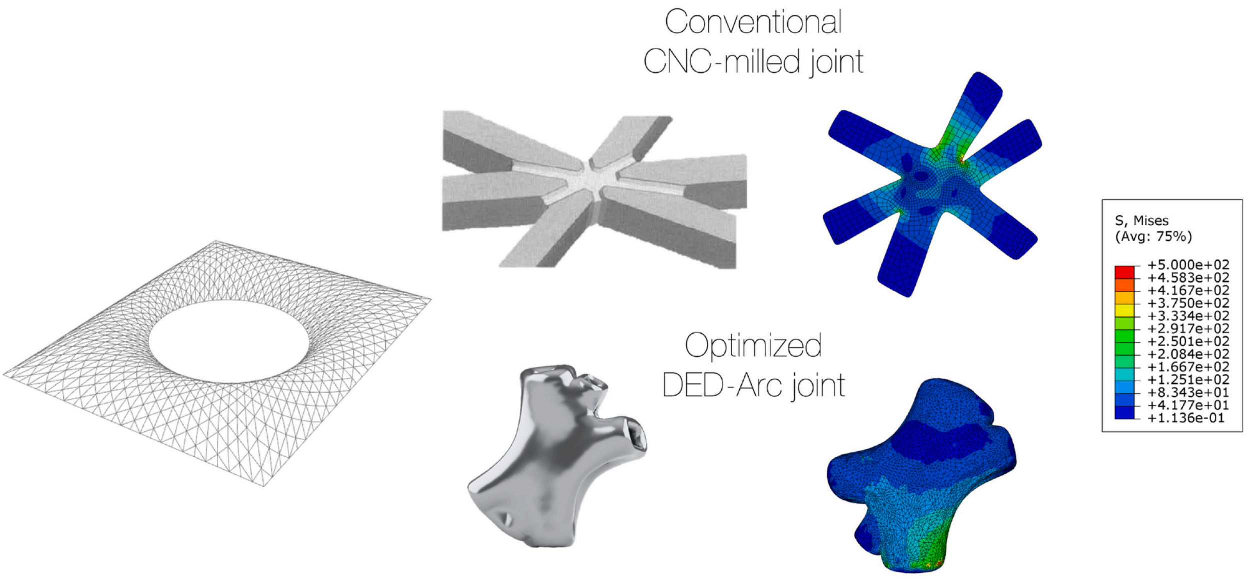


Fig. 3. Structural performances of conventional vs optimized joint.

were then evaluated for strength, stiffness and manufacturability. The workflow included: (i) the generation of a new class of topology-optimized joint designs using stiffness-based algorithms, (ii) an advanced Finite Element Analysis (FEA) to assess the joints performances under typical loading conditions, (iii) the evaluation of joint stiffness according to Eurocode 3, (iv) the adaptation of the final designs considering the manufacturing constraints of the selected technology. For the case study, DED-Arc manufacturing was considered to fabricate the optimized joints.

Multiple joint designs were generated, optimized and validated for both structural performances and manufacturability. By focusing on one typical 6-beams connection joint, FEA was performed considering typical loading conditions of the gridshell as well as local buckling failure (Fig. 3).

The optimized design resulted in a 12-mm thick shell-like stainless steel joint. This latter resulted having good structural performances with significantly reduced material use (40 kg vs 200 kg of the conventional CNC-milled joint). This reduction was achieved thanks to the combined use of topology optimization algorithms with DED-Arc manufacturing, able to fabricate complex-shaped shell-like steel elements ensuring good mechanical behavior.

4. Methodology

4.1. Objective of the work

The purpose of this study is to evaluate the environmental impact in terms of GWP of complex-shaped steel joints. The study is carried out as comparison between a conventional design and fabrication technique (CNC milling) with an optimized design and digital fabrication technique (DED-Arc manufacturing) to be potentially adopted in the future. The comparison is made on the case study of the gridshell rooftop of the Great Court of the British Museum. The analysis is carried in terms of both single joints (i.e., single conventional CNC-milled joint and single optimized DED-Arc joint) and whole batches (i.e., batch of conventional CNC-milled joints and batch of optimized DED-Arc joints). For the latter, a total of 1566 joints were considered, according to the real steel structure of the British Museum rooftop [24]. The objective is twofold: (i) to assess the potential impact of adopting DED-Arc manufacturing over conventional CNC milling to produce complex-shaped steel joints, and (ii) to quantify the improved environmental performances of topology-optimized joints over conventional ones.

4.2. Functional units

The environmental impact category selected as reference for the case study was GWP 100 in terms of kg CO_2e (i.e. kg of equivalent CO_2 emissions). For this aim, specific Environmental Product Declarations (EPDs) were researched. The EPDs are standardized documents that state the environmental performance of products and services. All the necessary EPDs were collected (Table 4 and 5) to calculate the environmental impact of each stage after researching through Ecoinvent dataset. From them, the GWP was calculated by multiplying the EPDs by either the amount of material (in kg) or the transportation distance (in km).

Two different functional units were adopted in the analysis: (i) 1 kg of fabricated part (either CNC milled or DED-Arc manufactured) and (ii) 1 complex-shaped structural joint. The former is used when comparing the environmental impact of the different production processes. The latter, instead, is used to compare the combined effect of design optimization and production process. For the latter, the conventional CNC-milled joint consists of a solid joint having 200-mm thickness and 200 kg of total weight [24]. The optimized DED-Arc manufactured joint is a shell-like joint having 12-mm thickness and 40 kg of total weight [21]. Some additional discussions were also made considering the whole batch of joints (for a total of 1566 joints).

4.3. System boundaries

Fig. 4 shows the system boundaries considering the following products: (i) single conventional CNC-milled joint, (ii) batch of conventional CNC-milled joints, (iii) single optimized DED-Arc joint, (iv) batch of optimized DED-Arc joints. For the latter, additional considerations were made for the case of on-site joint production and the case of adopting exclusively renewable energy as an electric source. In the system boundaries, all production processes are defined, specifying the ones either included in or excluded from production. Work processes and transportation phases are considered to count for their impact on CO_2 emissions. The definition of boundaries entails a series of assumptions that must be explicitly stated to enhance the validity of the results. Due

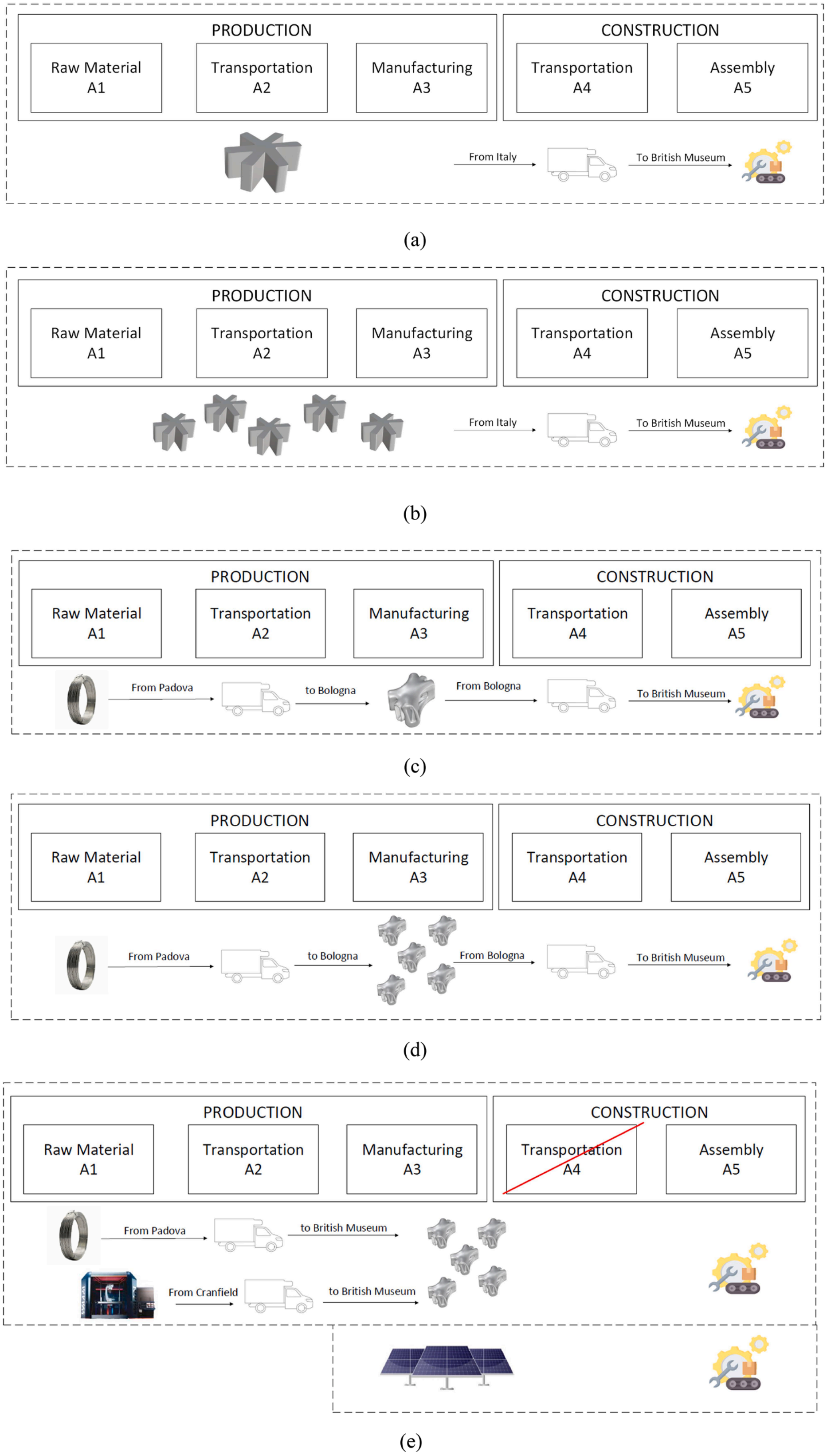


Fig. 4. Case study system boundaries: (a) single conventional CNC-milled joint, (b) batch of conventional CNC-milled joints, (c) single optimized DED-Arc joint, (d) batch of optimized DED-Arc joints, (e) batch of optimized DED-Arc joints considering on-site joint production and use of renewable energy.

Table 1
Data adopted for production of conventional CNC-milled joints.

Joint measure	Transportation	Construction
Single joint - CNC milled steel: *200 kg*	From Bologna to British Museum: *1648 km*	Assembly (semi-automatic scissors and welding): *4 kWh per joint*

Table 2
Data adopted for production of optimized DED-Arc joints.

Joint measure	Transportation	Manufacturing	Construction
Single joint – DED-Arc steel: *40 kg*	From Padova to Bologna: *121 km* From Bologna to British Museum: *1648 km* From Padova to British Museum: *1527 km* From Cranfield to British Museum: *80 km*	Argon:*0.517 kg per 1 kg* Energy: *3.07 kWh per 1 kg*	Assembly (semi-automatic scissors and welding): *4 kWh per joint*

to the complexity of the subject matter, it is often not possible to obtain all real data and EPDs. Defining how products and services are effectively processed is inherently complex and adapting them to case studies presents additional challenges.

For the production of CNC-milled joints, the manufacturing phase was analysed within a single EPD, given that no substantial information was provided in Ecoinvent database to assess the transportation impact in phase A2. This is due to the production framework adopted in the steel manufacturing company taken into account for the EPD, where no relocation is present from A1 to A3 as all processing operations are run internally. It should be noted that in phase A1 both raw material and plate transformation are included (as described in Fig. 2).

Regarding the DED-Arc production, the manufacturing phase is assumed to take place in Northern Italy, where technology providers of this manufacturing technique are present. This way, the results are more efficiently compared with the production of conventional CNC-milled joints, also assumed to occur in Northern Italy. Both products are then assumed to be transported from Northern Italy to London in phase A4.

A further case is considered for the production of optimized DED-Arc joints, to be located directly on-site. This aspect is possible thanks to the high flexibility of the DED-Arc set-up, which could be ideally placed directly on the construction site [23]. For this case, the DED-Arc set-up is assumed to be taken from Cranfield (UK), where a technology provider is present. Tables 1 and 2 provide the data adopted to calculate the GWP of both the conventional CNC-milled and optimized DED-Arc manufactured joints.

4.4. *Inventory analysis*

A significant portion of the analysis was conducted using the SimaPro software, which incorporates updated databases (Ecoinvent 3) to facilitate a more accurate selection of the EPDs. SimaPro is a LCA tool which allows to see, create and adjust detailed Life-Cycle Inventory (LCI) flows of materials and processes, and calculate their impact assessment by a method of choice (in this case, GWP100). Ecoinvent is a LCI database included in SimaPro [29]. Table 3 provides a detailed overview of all EPD sources.

Table 3
EPDs sources.

Material or Process	Source
Steel Production	SimaPro, Ecoinvent 3 versiom 5.3.0.0
Hot Rolling	SimaPro, Ecoinvent 2 version 3.0.140.1
Wire Drawing	SimaPro, Ecoinvent 2 version 15.3.1.0
Trucks	ICCT (International Council on Clean Transportation)
Argon	SimaPro, Ecoinvent 3 versiom 6.3.0.0
UK mixed electricity	RenSMART, The Renewable Energy Information Source
UK solar electricity	IPCC (Intergovernmental Panel on Climate Change)
Steel Plate	SimaPro, GaBi database
CNC (computer numerical control)	SimaPro, Ecoinvent database 2 version 3.3.1.0

Table 4
EPDs for CNC-milled single joint.

A1 - Raw Material Supply	A2 - Plant transportation	A3 - Manufacturing	A4 - Site transportation	A5 - Construction
	6.06 *kg CO_2e / kg*		Truck: *0.064 kg CO_2e / km*	UK Electricity: *0.281 kg CO_2e / kWh*

4.4.1. *CNC milling*

The conventional joint under study is manufactured using CNC milling. In the LCA analysis, the manufacturing process of the joint was subdivided into the following steps.

The first step is the plate manufacturing. From the EPD obtained from SimaPro software, data related to raw material extraction and all processes involved in plate production are included. Other consumption factors reported in the selected EPD are linked to the energy used by melting furnaces, water and transportation (Table 4).

The second step is the joint fabrication, in which CNC milling technology is employed to cut the components from the previously produced solid plates. From the EPD obtained from SimaPro, data related to recyclable scrap generated during CNC cutting, water used to refine cuts and lubricating oils are included. Both plate production and CNC milling occur within the same facility, thus reducing the stage A2.

The final step is the assembly phase, which involves the use of a lift to enable operators to reach the required height and welding to assemble the produced joints with the beams composing the gridshell (Table 4). This final step is the same also for the case of the optimized DED-Arc joint.

In the simulations conducted in SimaPro, material loss is inherently accounted in the definition of each EPD. Therefore, the environmental impact caused by the high presence of scrap material (resulting in high BTF ratio) is already accounted in the total GWP. In other cases, it is possible to perform a more refined analysis of the material utilization fraction by assessing the waste material beforehand, as demonstrated in [22].

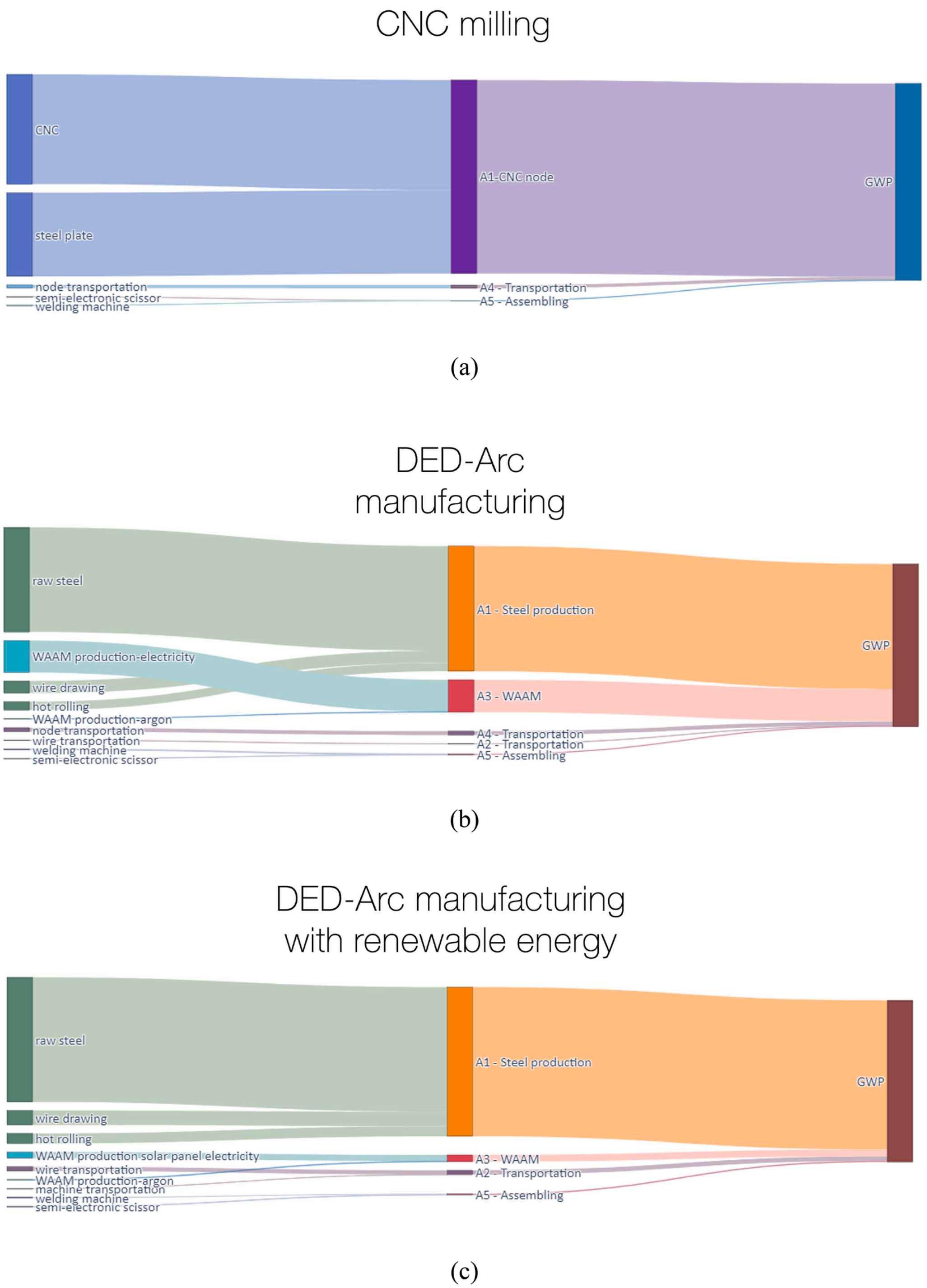
4.4.2. *DED-Arc manufacturing*

The optimized joint under study is manufactured using DED-Arc fabrication. In the LCA analysis, the manufacturing process of the joint was subdivided into the following steps.

The first step is the wire fabrication, for which it was deemed necessary to conduct a detailed study for all processes involved. In detail, the extraction and production of steel was obtained from a specific EPD providing a comprehensive description of the production

Table 5
EPDs for optimized DED-Arc single joint.

A1 - Raw Material Supply	A2 - Plant transportation	A3 - Manufacturing	A4 - Site transportation	A5 - Construction
Steel production: *2.83 kg CO_2e / kg* Hot rolling: *0.226 kg CO_2e / kg* Wire drawing: *0.327 kg CO_2e / kg*	Truck: *0.064 kg CO_2/t km*	Argon: *1.33 kg CO_2e / kg* UK Mixed Electricity: *0.281 kg CO_2e / kWh* UK Solar Electricity: *0.046 kg CO_2e / kWh*	Truck: *0.064 kg CO_2e / km*	UK Electricity EPD: *0.281 kg CO_2e / kWh*



(a)

(b)

(c)

Fig. 5. Material flows for the production of 1 kg of steel joint produced with: (a) CNC milling, (b) DED-Arc manufacturing, (c) DED-Arc manufacturing using renewable energy.

process. This includes extraction, loading of raw materials into the furnace, melting and refining. The process also involves the slag removal. Additionally, the selected EPD specifies for the employment of both electric arc melting and oxygen burner melting methods. It also accounts for furnace maintenance and chemical inspection.

The second step is hot rolling, including scarfing, grinding, pickling and finishing. The wire production occurs during the wire drawing phase, which produces the final diameter of 1–2 mm.

The manufacturing step is performed through DED-Arc process. During the additive manufacturing phase, two main factors are identified in the environmental impact: (i) the electricity consumption and (ii) the use of inert gas for arc ignition of the welding process. Focusing on the analysis of electricity consumption, it was deemed appropriate to adopt the values already tested in the study by Bekker et al. [22], which reports an energy consumption of 3.07 kWh per kg of printed product, considering a production rate of 1 kg/h. This value includes the power required for welding, robotic arm movement and fume extraction. The EPD for electricity was determined based on data from the United Kingdom, where electricity is generated from a mix of renewable and non-renewable energy sources (Table 5). Regarding the inert gas used in welding, the study adopts the values referred in [22], which assumed an Argon consumption of 0.517 kg per kg of printed product (Table 5). An appropriate EPD was assigned to this value, sourced from the Ecoinvent database.

The next steps are the joint transportation and assembly, following the same approach as the one adopted for the conventional CNC-milled joint (Section 4.4.1). It should be noted that in this study a great simplification was made assuming that the whole batch of 1566 joints (both conventional CNC-milled ones and optimized DED-Arc ones) would be transported on a single truck load. Alothough this latter assumption is far from a real scenario, it was assumed to be negligible given the very small impact of transportation on the overall GWP of the joints production.

Given that one of the advantages of DED-Arc manufacturing is the possibility to move the production directly on-site, a parallel study was carried out simulating that the transportation of a 3D printer would take place to the construction site.

Another great advantage of DED-Arc manufacturing lies within the possibility to reduce the environmental impact of the manufacturing stage (A3) through the exclusive adoption of renewable energy as primary electrical energy input. Indeed, the energy production plays a decisive role in the overall GWP of the joints production, as it will be seen in Section 5. For this reason, a parallel study was conducted assuming the exclusive use of renewable energy for the manufacturing process. For this, the EPD related to the IPCC (Intergovernmental Panel on Climate Change) was taken as input parameter to assess the GWP related to the use of solar electricity in the UK.

5. Results and discussion

5.1. Influence of 3D printing vs conventional manufacturing

Fig. 5 reports the Sankey diagrams for the production of 1 kg of steel joint produced with CNC milling (Fig. 5a), DED-Arc manufacturing (Fig. 5b) and DED-Arc production with renewable energy (Fig.5c). The Sankey diagrams are commonly adopted to show the flow of materials from the resource types to the life-cycle stages (A1-A5, according to ISO 14040). Given the normalized values of GWP, these results account only for the different manufacturing technology considered. Hence, these values describe the impact of adopting DED-Arc manufacturing versus conventional manufacturing techniques, such as CNC milling.

From the reported diagrams, it is clear that the vast majority of consumption for the CNC milling production is caused by both the steel plate production and the CNC milling. This latter significantly contributes to the overall GWP of the whole joint production due to the high rate of material scrap produced during this step. Indeed, previous work reports 0.50 material utilization fraction for the sole step of CNC milling (i.e., 2 kg of the original product are required to produce 1 kg of final product) [22].

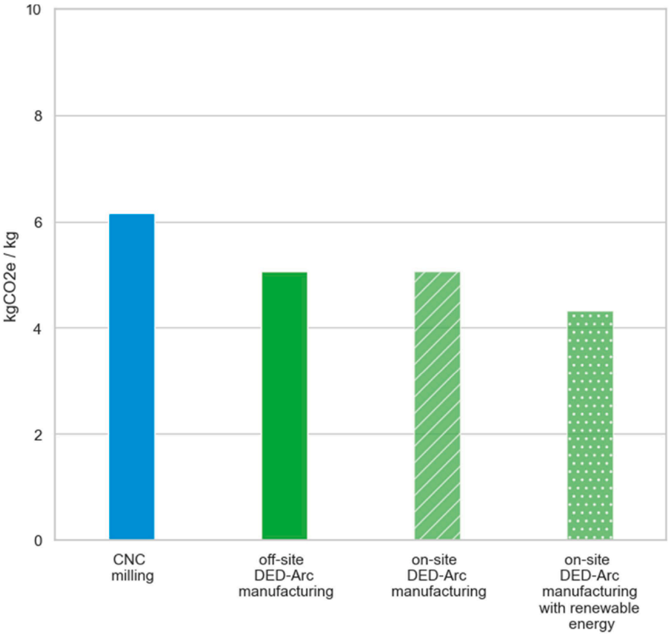


Fig. 6. Comparison of different fabrication scenarios for the production of complex-shaped steel joints.

Regarding DED-Arc manufacturing, the two main sources of impact in terms of GWP are the raw steel production and the electricity consumption during the part manufacturing. For the former, optimization techniques to reduce the material consumption are recommended to reduce the overall environmental impact of the produced part (as discussed in Section 6). For the latter, additional considerations on the use of renewable energy are made to further reduce the overall GWP of the produced part (as discussed in Section 5.3). Fig. 5c reports the Sankey diagram for 1 kg of steel joint produced with DED-Arc manufacturing considering the use of renewable energy during the manufacturing stage. This contributes significantly to the reduction of impact of the part manufacturing stage, thus focusing most of the environmental impact on the raw material (steel) production.

5.2. Influence of off-site vs on-site manufacturing

Fig. 6 compares the GWP in terms of mass normalized of four different fabrication scenarios: (i) CNC milling, (ii) off-site DED-Arc manufacturing, (iii) on-site DED-Arc manufacturing and (iv) on-site DED-Arc manufacturing with renewable energy. By comparing the same amount of part produced, CNC milling results in higher normalized GWP compared to all scenarios where DED-Arc manufacturing is adopted. Again, this result could be attributed to the significant BTF ratio associated to the CNC milling production.

In detail, in terms of mass normalized, off-site DED-Arc manufacturing production results in 29% reduction with respect to CNC milling production. On-site DED-Arc manufacturing production does not result in any significant change in the overall GWP (0.3% difference with respect to off-site DED-Arc manufacturing). The slight difference in value is primarily due to the reduction of impact associated with the part transportation (A4). Obviously, this scenario cannot be created for CNC milling, as the type of process would require a dedicated manufacturing facility.

The fourth scenario consisted in on-site DED-Arc manufacturing with the exclusive use of renewable energy for the manufacturing stage. For

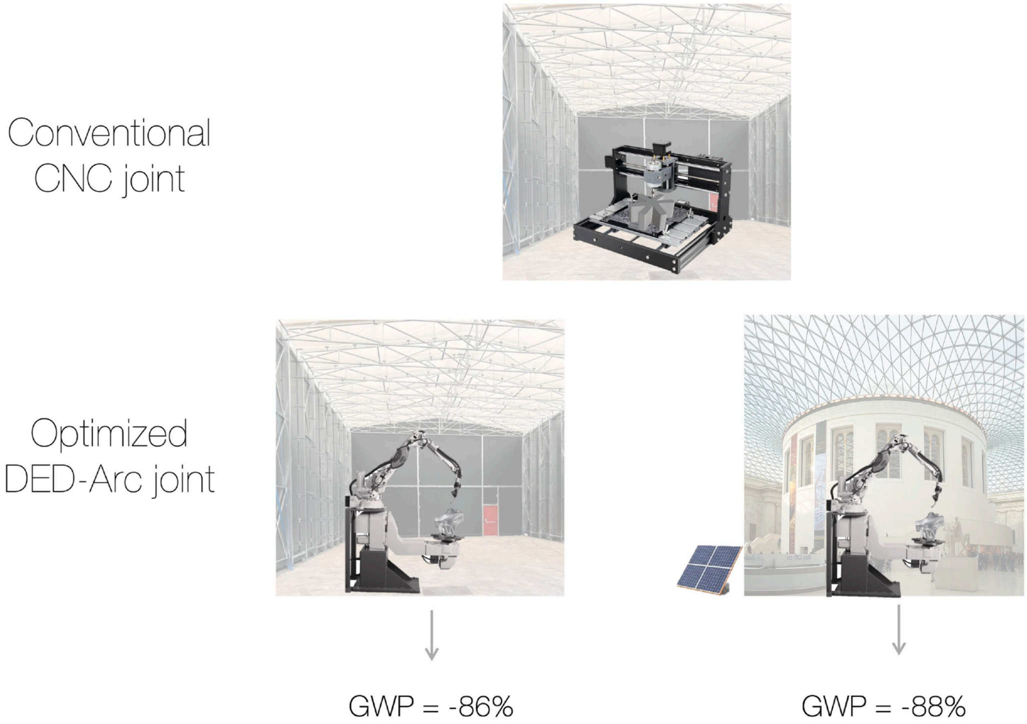


Fig. 7. Comparison on CNC milling production with DED-Arc off-site and on site assuming the use of renewable energy.

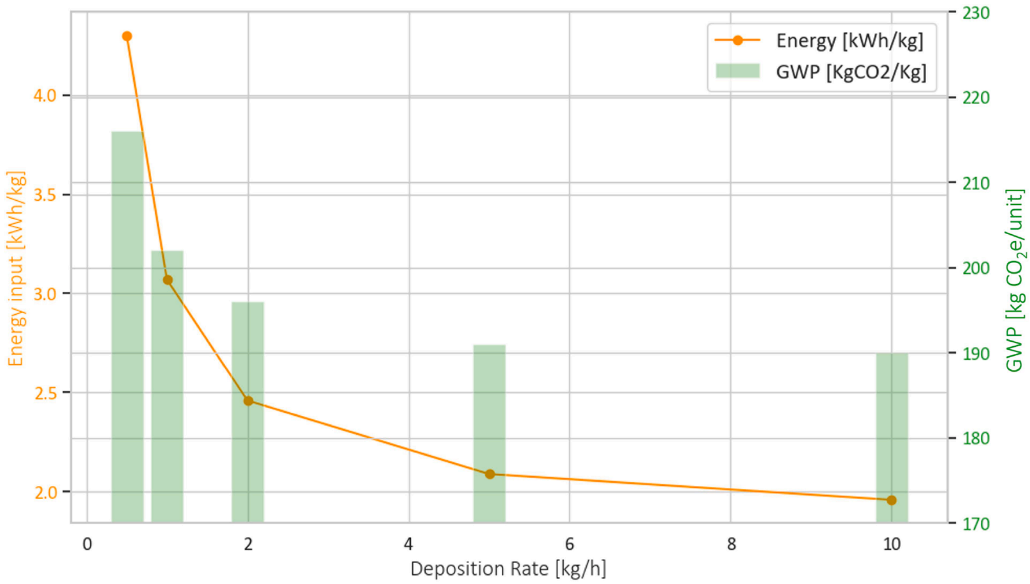


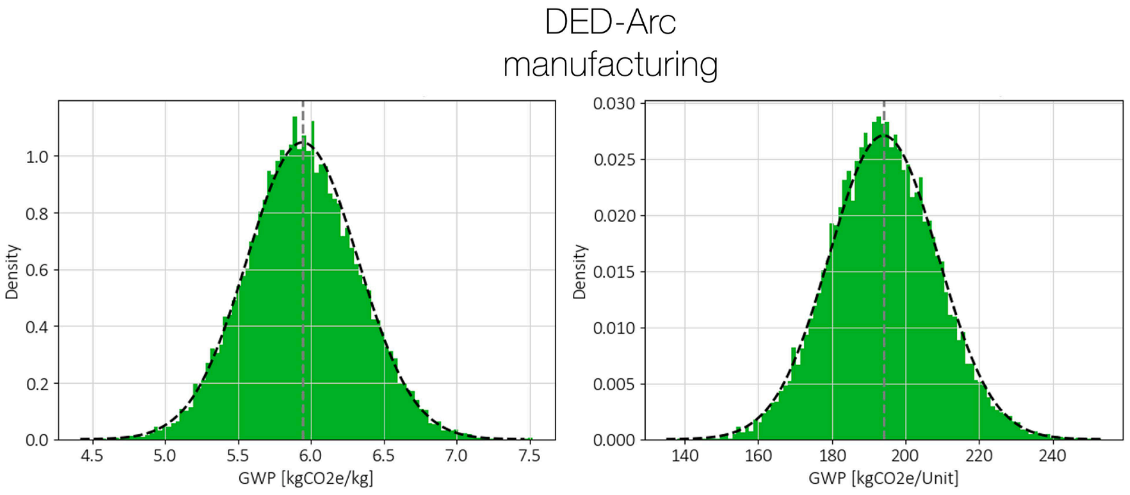
Fig. 8. Influence of deposition rate on the environmental impact of the production of one optimized DED-Arc joint.

this scenario, the GWP in terms of kg CO$_2$e / kg part produced is reduced by 41% with respect to the benchmark scenario (i.e. fabrication by CNC milling). Therefore, by considering only the fabrication process itself, DED-Arc manufacturing could potentially reduce the environmental impact of the production of complex-shaped steel joints by 41%.

Fig. 7 compares the GWP of the three most significant scenarios: (i) the benchmark, i.e. production of the conventional joints with CNC milling, (ii) the off-site production of the optimized joints via DED-Arc manufacturing and (iii) the on-site production of the optimized joints via DED-Arc manufacturing considering the exclusive use of renewable energy. The environmental impact was computed considering the production of the whole batch of joints for the case study of the rooftop of the British Museum (1566 joints). The calculation also accounts for the optimization process of the joints, which reduced the weight from the conventional one up to 80% (see Section 3). The combined effect of topology optimization and digital fabrication resulted in a global reduction of GWP of 86% (increased up to 88% if considering the exclusive use of renewable energy). This latter aspect will be analysed in detail in Section 6.

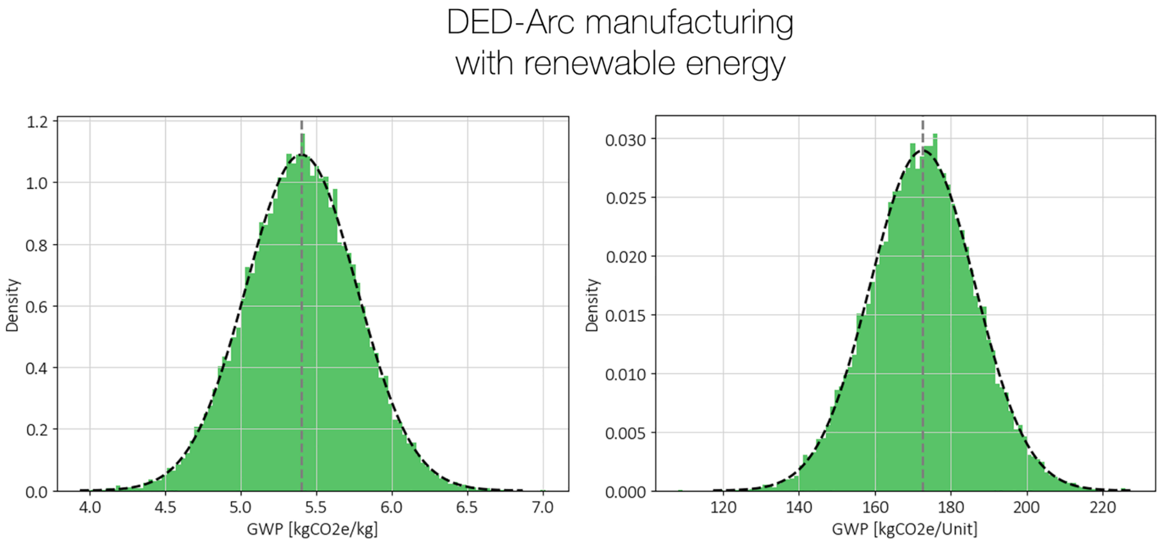
5.3. *Influence of deposition rate*

Metal 3D printing technology, and in particular DED-Arc manufacturing, presents high versatility in the production phase,



(a) (b)

Fig. 9. Sensitivity analysis on the deposition rate for DED-Arc manufacturing: (a) per kg of printed part, (b) per single joint produced.



(a) (b)

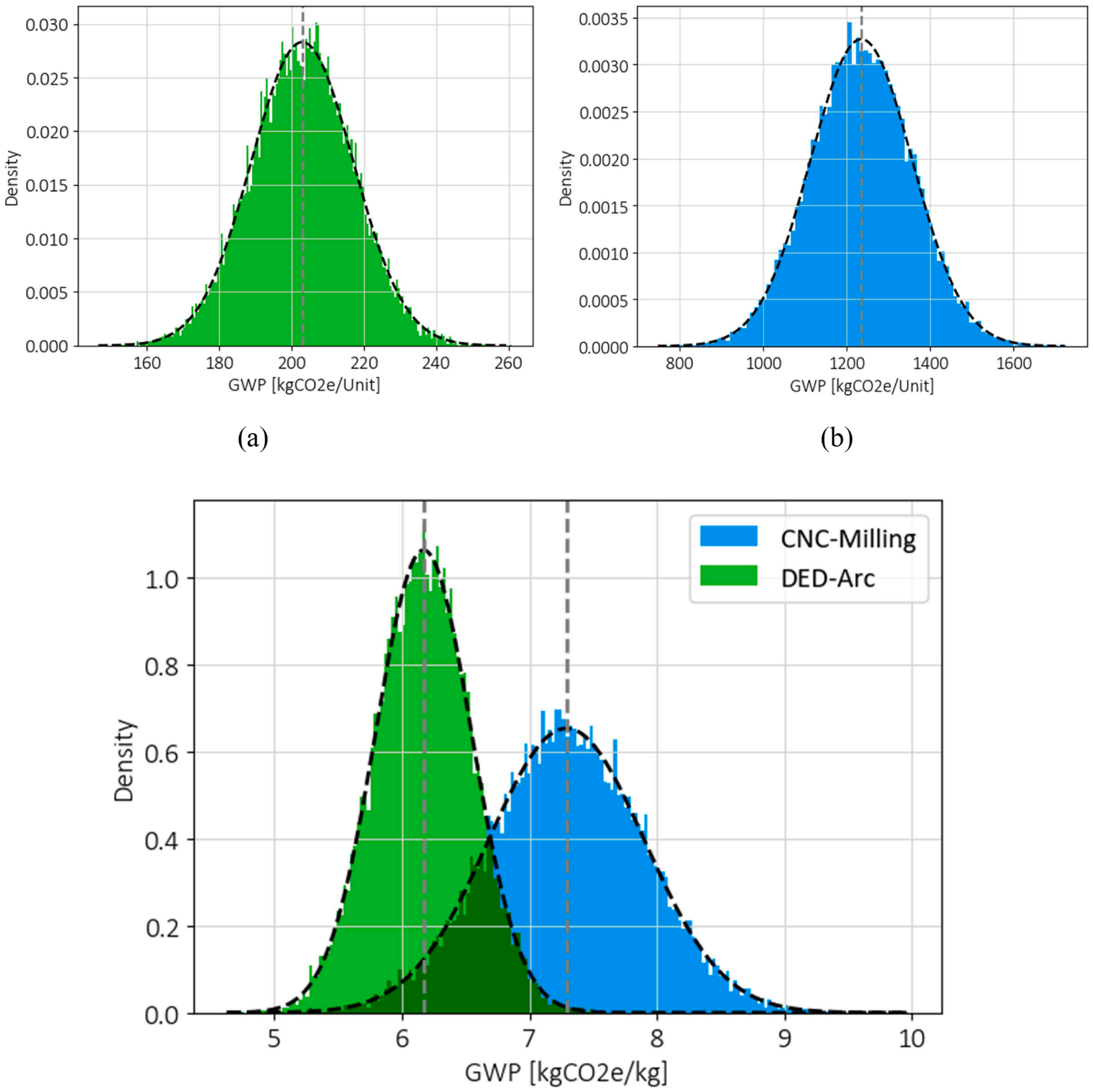
Fig. 10. Sensitivity analysis on the deposition rate for DED-Arc manufacturing with the exclusive use of renewable energy: (a) per kg of printed part, (b) per single joint produced.

allowing for the fine tuning of a wide range of process parameters. This versatility represents a technical advantage, although implying that the environmental impact associated with production can vary significantly depending on the process inputs. Among these, the deposition rate plays a crucial role in identifying both the environmental impact and the production cost of the printed parts, due to the direct correlation between the deposition rate and the energy input associated to the fabrication process.

Fig. 8 presents the relationship between the deposition rate (in kg/h), the energy input associated to the fabrication (in kWh/kg) and the resulting GWP in terms of kgCO$_2$e/unit. In this case, the unit is referred to as the single joint produced. The deposition rate was varied between 0.5 kg/h and 10 kg/h, according to the study carried out by Shah et al. [20]. Within this range, the GWP associated to the production of one optimized joint varied between 190 kgCO$_2$e (for a deposition rate of 10 kg/h) and 215 kgCO$_2$e (for a deposition rate of 0.5 kg/h). Hence, the LCA was carried out considering a deposition rate of 1 kg/h.

Considering the high influence of the deposition rate in the energy input within the fabrication process, a Monte Carlo simulation was developed to tackle this issue from a probabilistic perspective. The objective was to understand the impact in terms of GWP 100 resulting from the LCA presented in Section 4 in response to the variability of the deposition rate (significantly affecting the A3 stage). Two limiting scenarios were studied: (i) DED-Arc production and (ii) DED-Arc production considering the exclusive use of renewable energy as energy input. For both scenarios, the analysis was carried out considering both 1 kg of printed material and the single optimized joint as functional unit, respectively. The Monte Carlo analysis method is used to perform the sensitivity analysis in Python. The Monte Carlo method is a mathematical technique that estimates a set of possible outcomes (in this case, the environmental impact estimated in terms of GWP 100) and their probability of occurrence by varying the input parameters in their estimated interval of values. Within the analysis, a model is simulated for a large number of iterations, in which a random value for each input parameter is assigned. The result is a set of outcomes and probabilities of their occurrence, taking into consideration the impact of the input parameter within the overall outcome.

The Monte Carlo analysis was carried out considering the deposition



(a)

(b)

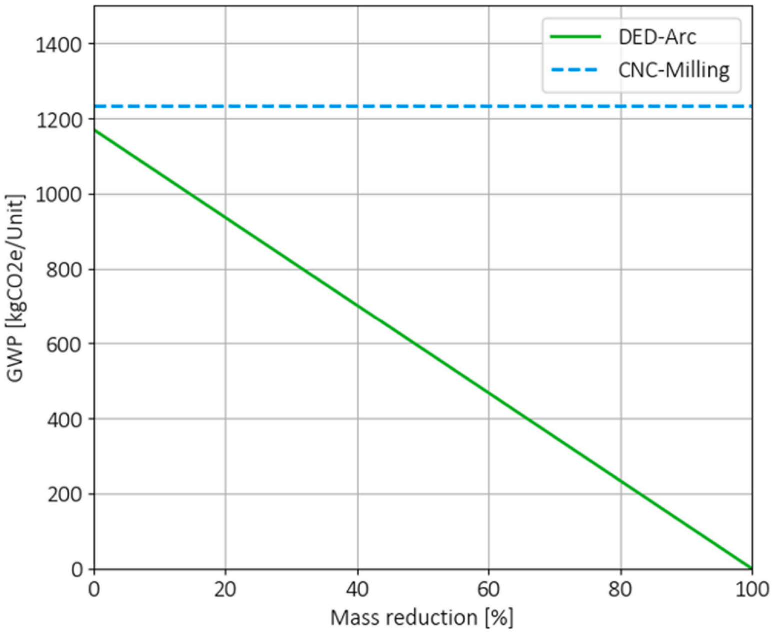
(c)

Fig. 11. Uncertainty analysis for (a) DED-Arc and (b) CNC-milling per single joint produced; (c) uncertainty analysis per kg of part produced.

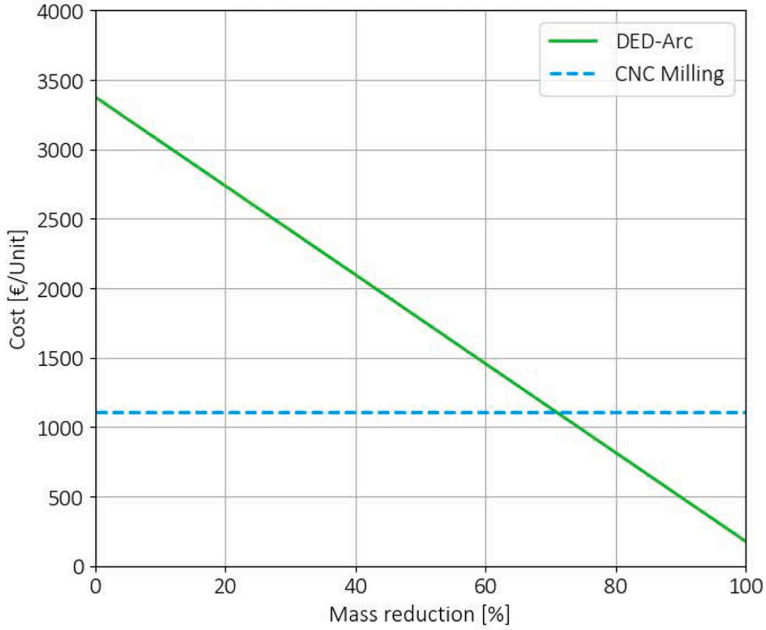
rate as input parameter, whose minimum and maximum values were set equal to 0.5 kg/h and 10 kg/h, respectively. The analysis was repeated for 20,000 iterations. The results are reported in Figs. 9 and 10 for the two considered scenarios and the two functional units. The results confirm that the environmental impact of DED-Arc manufacturing is significantly affected by the deposition rate, resulting in a range of values between 170 kgCO_2e and 218 kgCO_2e (considering the 5% and 95% distribution fractiles) for the DED-Arc production scenario. The values lower significantly when considering the scenario of DED-Arc production with the exclusive use of renewable energy, between 125 kgCO_2e and 170 kgCO_2e (considering the 5% and 95% distribution fractiles).

5.4. *Uncertainty analysis*

Given the high influence of the input parameters on the environmental assessment presented in this work, an uncertainty analysis was carried out to compare the effectiveness of DED-Arc manufacturing vs CNC milling. The objective was to compare the GWP 100 of the LCA presented in Section 4 for the two scenarios of DED-Arc manufacturing and CNC milling accounting for the uncertainties related to the input parameters. The analysis was performed considering both the single unit production (i.e. single conventional CNC-milled joint and single optimized DED-Arc joint) and 1 kg of part produced. A normal distribution with a coefficient of variation of 10% was considered for each input inventory in the LCA, according to the analysis carried out by Kokare et al. [30]. The Monte Carlo analysis was repeated for 20,000 iterations. The results are illustrated in Fig. 11. Concerning the environmental impact per kg of part produced (Fig. 11c), the distribution of values for CNC milling is more dispersed than for the DED-Arc manufacturing, thus resulting in a higher variability of the former when considering the uncertainty related to the input parameters of the LCA. For both production processes, the environmental impact per part produced lies in the following ranges: between 180 and 226 kgCO_2e for the optimized



(a)



(b)

Fig. 12. Correlation between: (a) mass reduction and GWP; (b) mass reduction and production cost.

DED-Arc joint and between 1035 and 1435 $kgCO_2e$ for the conventional CNC-milled joint.

6. Combined effect of design optimization and DED-arc manufacturing

The adoption of optimized design solutions in structural systems would result in overall increase in material utilization and hence mass savings [31]. Recent work demonstrated the effectiveness of combining metal 3D printing and topology optimization to reduce the environmental impact of steel structures. Shah et al. [20] compared the environmental impact of different optimized steel beams to be produced with WAAM (or DED-Arc) compared to the conventional I-beam section. The results demonstrated that by achieving a 50% mass reduction, the WAAM optimized beam impacted less than the conventional I-beam.

This work aims at evaluating the combined effect of design optimization and DED-Arc manufacturing compared to conventional design produced with CNC milling, as usually adopted to produce complex-shaped steel joints. Fig. 12a presents the correlation between mass reduction and GWP for both CNC milling and DED-Arc manufacturing. Considering the framework presented in Section 4, the graph confirms the findings of Section 5, resulting in DED-Arc manufacturing being less environmentally impactful than CNC milling even without accounting for any mass reduction. This result could be due to the high BTF ratio associated with CNC milling, resulting in much higher environmental impact with respect to the additive manufacturing process.

Based on the economic inventory proposed by Kokare et al. [30], a correlation analysis between mass reduction and production cost was carried out (Fig. 12b). The results show a break-even point between CNC milling and DED-Arc manufacturing when achieving 70% of mass reduction. This suggests that for highly optimized components, additive manufacturing not only offers environmental advantages (as shown in the first graph) but can also be more economically viable than conventional manufacturing processes adopted for complex-shaped geometries.

It should also be noted that the high production cost associated to the DED-Arc manufacturing could be significantly decreased in the future, when this advanced technology will be more widely adopted in the market.

7. Conclusions and future outlook

The study presents an investigation on the potential benefit of adopting combined optimization strategies and large-scale additive manufacturing solutions to reduce the environmental impact of complex-shaped steel joints in construction.

The analysis was based on a comparison between Computer Numerically Controlled (CNC) milling technology and a large-scale metal 3D printing technique referred to as Wire-Arc Additive Manufacturing (WAAM) or DED-Arc manufacturing. Both fabrication techniques were compared on the case study of the production of steel joints for the realization of the gridshell rooftop on the Great Court of the British Museum in London. The environmental impact was assessed considering both the influence of the production technologies and the combined effect when design optimization is also implemented. For this, a topology-optimized steel joint suitable for fabrication with DED-Arc is compared with the conventional CNC-milled joint adopted for the gridshell structure of the British Museum.

The environmental impact was assessed in terms of Global Warming Potential (GWP) through a cradle-to-completion Life-Cycle Assessment (LCA) considering various aspects and scenarios affecting the analysis.

The following results were obtained:

- By comparing the production via CNC milling and DED-Arc manufacturing, the latter resulted to have a lower environmental impact with respect to the more commonly adopted fabrication process for complex-shaped parts. This result could be attributed to the high buy-to-fly (BTF) ratio attributed to CNC milling, causing high metal scrap rate with respect to the high material utilization fraction of metal 3D printing technologies.
- Considering DED-Arc manufacturing, the flexibility of this production process was investigated assuming different scenarios, such as the on-site production and the exclusive use of renewable energy. Additional sensitivity analysis was carried out on the adopted deposition rate, which could affect the overall environmental impact. Further investigations considering the exclusive use of renewable energy resulted to be less affected by any source of variation related to the production process.
- Uncertainty analysis using the Monte Carlo method was performed to study the effect of uncertainty in input data on the environmental impact of both CNC milling and DED-Arc manufacturing. The results revealed a slightly higher sensitivity to the input uncertainty on CNC milling with respect to DED-Arc manufacturing.
- The combined use of design optimization and DED-Arc manufacturing was investigated in terms of environmental and economic impact. The results revealed that the environmental impact of DED-Arc manufacturing is always lower than for CNC milling, due to the high BTF ratio related to the latter. Regarding the economic impact, DED-Arc manufacturing resulted to be more economically viable than CNC milling for designs having 70% or higher mass savings.

These first results revealed the dual benefit of adopting topology optimization design strategies and large-scale additive manufacturing technologies to produce complex-shaped parts for steel construction. Future works should include a wider range of geometries, materials and cradle-to-grave system limits.

CRediT authorship contribution statement

Vittoria Laghi: Writing – original draft, Validation, Supervision, Conceptualization. **Elisabetta Savino:** Writing – original draft, Investigation, Conceptualization. **Giada Gasparini:** Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

References

[1] OECD, Environment At a Glance 2020, OECD, 2020, https://doi.org/10.1787/4ea7d35f-en.

[2] International Energy Agency, Iron and Steel Technology Roadmap, 2020. https://www.iea.org/reports/iron-and-steel-technology-roadmap (accessed September 26, 2023).

[3] M. Bi, P. Tran, L. Xia, G. Ma, Y.M. Xie, Topology optimization for 3D concrete printing with various manufacturing constraints, Addit Manuf 57 (2022) 102982, https://doi.org/10.1016/J.ADDMA.2022.102982.

[4] M.S.I. Smith, D. Fang, C. Mueller, J.V. Carstensen, Reducing embodied carbon with material optimization in structural engineering practice: perceived barriers and opportunities, J. Build. Eng. 95 (2024), https://doi.org/10.1016/j.jobe.2024.109943.

[5] A. Aramcharoen, P.T. Mativenga, Critical factors in energy demand modelling for CNC milling and impact of toolpath strategy, J Clean Prod 78 (2014) 63–74, https://doi.org/10.1016/J.JCLEPRO.2014.04.065.

[6] Y. Zhang, L. Wu, X. Guo, S. Kane, Y. Deng, Y.G. Jung, J.H. Lee, J. Zhang, Additive Manufacturing of Metallic Materials: a Review, J Mater Eng Perform 27 (2018) 1–13, https://doi.org/10.1007/s11665-017-2747-y.

[7] M. Sauerwein, E. Doubrovski, R. Balkenende, C. Bakker, Exploring the potential of additive manufacturing for product design in a circular economy, J Clean Prod 226 (2019) 1138–1149.

[8] C. Buchanan, L. Gardner, Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges, Eng Struct 180 (2019) 332–348, https://doi.org/10.1016/j.engstruct.2018.11.045.

[9] A. Kanyilmaz, A.G. Demir, M. Chierici, F. Berto, L. Gardner, S.Y. Kandukuri, P. Kassabian, T. Kinoshita, A. Laurenti, I. Paoletti, A. du Plessis, S.M.J. Razavi, Role of metal 3D printing to increase quality and resource-efficiency in the construction sector, Addit Manuf 50 (2022), https://doi.org/10.1016/j.addma.2021.102541.

[10] L. Gardner, P. Kyvelou, G. Herbert, C. Buchanan, Testing and initial verification of the world's first metal 3D printed bridge, J Constr Steel Res 172 (2020), https://doi.org/10.1016/j.jcsr.2020.106233.

[11] LASIMM project, (n.d.). https://www.lasimm.eu, (n.d.). (accessed December 19, 2024).

[12] INTEGRADDE project, (n.d.). http://www.integraddeproject.eu (accessed December 19, 2024).

[13] MARILIGHT project, (n.d.). https://marilight.net (accessed December 19, 2024).

[14] V. Laghi, G. Gasparini, Explorations of efficient design solutions for Wire-and-Arc Additive manufacturing in construction, Structures 56 (2023) 104883, https://doi.org/10.1016/J.ISTRUC.2023.104883.

[15] M. Chierici, F. Berto, A. Kanyilmaz, Resource-efficient joint fabrication by welding metal 3D-printed parts to conventional steel: a structural integrity study, Fatigue Fract Eng Mater Struct 44 (2021) 1271–1291, https://doi.org/10.1111/FFE.13428.

[16] G. Campatelli, F. Montevecchi, G. Venturini, G. Ingarao, P.C. Priarone, Integrated WAAM-Subtractive Versus Pure Subtractive Manufacturing Approaches: an Energy Efficiency Comparison, Int. J. Precis. Eng. Manuf. - Green Technol. 7 (2020) 1–11, https://doi.org/10.1007/S40684-019-00071-Y.

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

[18] L. Li, M. Dias, J.P.M. Pragana, B. Ferreira, I. Ribeiro, C.M.A. Silva, Economic and Environmental Potential of Wire-Arc Additive Manufacturing, (2022). https://doi.org/10.3390/su14095197.

[19] S. Kokare, J. Shen, P.P. Fonseca, J.G. Lopes, C.M. Machado, T.G. Santos, J. P. Oliveira, R. Godina, Wire arc additive manufacturing of a high-strength low-alloy steel part: environmental impacts, costs, and mechanical properties, Int. J. Adv. Manuf. Technol. 134 (2024) 453–475, https://doi.org/10.1007/s00170-024-14144-z.

[20] I.H. Shah, N. Hadjipantelis, L. Walter, R.J. Myers, L. Gardner, Environmental life cycle assessment of wire arc additively manufactured steel structural components, J Clean Prod 389 (2023) 136071, https://doi.org/10.1016/J.JCLEPRO.2023.136071.

[21] V. Laghi, N. Babovic, E. Benvenuti, H. Kloft, Blended structural optimization of steel joints for Wire-and-Arc Additive Manufacturing, Eng Struct 300 (2024) 117141, https://doi.org/10.1016/J.ENGSTRUCT.2023.117141.

[22] A.C.M. Bekker, J.C. Verlinden, Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel, J Clean Prod 177 (2018) 438–447, https://doi.org/10.1016/J.JCLEPRO.2017.12.148.

[23] S.I. Evans, J. Wang, J. Qin, Y. He, P. Shepherd, J. Ding, A review of WAAM for steel construction – Manufacturing, material and geometric properties, design, and future directions, Structures 44 (2022) 1506–1522, https://doi.org/10.1016/J.ISTRUC.2022.08.084.

[24] J. Sischka, Engineering the Construction of the Great Court Roof For the British Museum, Widespan Roof Structures, 2000, p. 199.

[25] Euopean Committee for Standardization, EN ISO 14040 - Environmental management – Life cycle Assessment – Principles and Framework, BSI Standards Limited, 2020.

[26] European Committee for Standardization, EN ISO 14044 - Environmental management. Life cycle assessment. Requirements and Guidelines, British Standards Institution, 2021.

[27] European Committee for Standardization, EN 15804 - Sustainability of construction works. Environmental Product declarations. Core rules For the Product Category of Construction Products, British Standards Institution, 2014.

[28] V. Laghi, M. Palermo, M. Bruggi, G. Gasparini, T. Trombetti, Blended structural optimization for wire-and-arc additively manufactured beams, Prog. Addit. Manuf. (2022), https://doi.org/10.1007/s40964-022-00335-1.

[29] PRé Sustainability, SimaPro Database Manual Methods Library, (2021). https://simapro.com/wp-content/uploads/2021/12/DatabaseManualMethods930.pdf (accessed April 7, 2025).

[30] S. Kokare, J.P. Oliveira, R. Godina, A LCA and LCC analysis of pure subtractive manufacturing, wire arc additive manufacturing, and selective laser melting approaches, J Manuf Process 101 (2023) 67–85, https://doi.org/10.1016/J.JMAPRO.2023.05.102.

[31] O. Ibhadode, Z. Zhang, J. Sixt, K.M. Nsiempba, J. Orakwe, A. Martinez-Marchese, O. Ero, S.I. Shahabad, A. Bonakdar, E. Toyserkani, Topology optimization for metal additive manufacturing: current trends, challenges, and future outlook, Virtual Phys Prototyp 18 (2023), https://doi.org/10.1080/17452759.2023.2181192.