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Comparative Life Cycle Assessment of novel steel section design with Wire Arc Additive Manufacturing

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ABSTRACT

Additive manufacturing, particularly Wire Arc Additive Manufacturing (WAAM), is emerging as a promising technology in the construction sector due to its potential to reduce environmental impacts. Life Cycle Assessment (LCA) is a crucial methodology for evaluating the environmental footprint of products and processes, that can be carried out from raw material extraction to the end of production, commonly referred to as "cradle-to-gate" analysis. This study focuses on the environmental impact of 3D-printed steel elements using WAAM technology for construction applications. Specifically, the conventional production of Circular Hollow Section (CHS) steel components was compared with the innovative production of Tubular Sandwich Section (TSS) steel components using WAAM. The analysis provides a comparison of the carbon footprint associated to both production methods, highlighting in detail the emissions factors associated with each step of the WAAM production. The results highlighted that WAAM not only offers design and structural benefits to build complex-shaped geometries but also contributes to more sustainable construction practices with a lower "cradle-to-gate" carbon footprint due to the reduced material consumption associated with material efficiency.

Keywords: Life-Cycle Assessment, Wire-Arc-Additive Manufacturing, Optimization

1. Introduction

The global steel demand has been rising significantly in recent years, leading to increased CO_2 emissions from the iron and steel sector. Although the direct CO_2 intensity of crude steel production has slightly decreased in recent years, efforts must be accelerated to align with the Net Zero Emissions by 2050 (NZE) Scenario. Material efficiency strategies are essential to balance demand growth by reducing losses and optimizing steel use throughout the value chain, without compromising the quality of the end-use service. This is crucial for the steel sector to stay on track with the NZE Scenario. While scrap-based steel production is less energy-intensive compared to primary production from iron ore, the emission reduction potential of conventional processes and scrap is limited. Thus, innovation in steel production will be vital in the coming decade to commercialize new near-zero-emission processes [1].

In this context, metal Additive Manufacturing (AM), particularly Wire Arc Additive Manufacturing (WAAM), presents a promising solution. WAAM enables the production of large-scale structural elements with complex geometries that are either impossible to achieve with conventional production methods or would require complex welding. It is the most suitable AM technology for large-scale elements because it offers high deposition rate that can exceed 9.5 kg/h [2]. It offers benefits such as reduced material consumption, design freedom, and higher material efficiency, enabling the production of structural elements with topologically optimized geometries. The integration of WAAM technology with advancements in Computer-Aided Design (CAD) and three-dimensional modeling paves the way for exploring novel, optimized structural elements.

Traditionally, Circular Hollow Section (CHS) members are adopted in various applications due to their compact and bi-symmetrical cross-sectional shape, making them ideal for structures subjected to high axial loads and radial pressures. However, creating complex geometries and strengthening CHS members require complex welding.

Consequently, this work focuses on a novel cross-section known as Tubular Sandwich Section (TSS), which is particularly suited for applications in offshore engineering and building construction. The TSS combines the advantages of conventional CHS with the capabilities of WAAM technology to produce stronger and stiffer cross-sections reducing material consumption. The TSS provides greater design freedom to create structurally efficient elements optimized for specific performance targets, particularly in resisting buckling failure [3].

Despite the advantages associated with WAAM production, attention to its environmental impact is needed due to the additional production steps compared to conventional methods, such as wire drawing and arc welding, which result in additional energy consumption and emissions associated with these processes. This aspect has been the focus of recent research on the environmental impact of WAAM, comparing conventional and WAAM production processes for various metal elements [4–9]. However, limited research has been conducted on the environmental impact of metal WAAM elements for structural applications [10].

The study focuses on a comparative "cradle-to-gate" analysis of cold formed structural steel CHS and WAAM steel TSS. The environmental impact of these two products manufactured using different methods, conventional cold forming for CHS and WAAM for TSS, has been computed. The study aims to highlight the potential advantages offered by adopting WAAM to manufacture steel structural elements.

2. Methodology

2.1. Functional unit

The environmental impact of two different tubular structural elements has been assessed for comparison purposes. Mass production has been considered for both productions. The first element is a cold formed Circular Hollow Section (CHS) with a nominal diameter of 1412 mm, a thickness of 12.8 mm and a length of 2 m (Fig. 1a). The second element is a novel cross-section, referred to as Tubular Sandwich Section (TSS), initially introduced by some of the authors in [3]. This innovative design is optimized to offer mechanical advantages over the CHS, particularly regarding local buckling and radial pressure, as detailed in [3], where interested readers can explore further details outside the scope of this work. As illustrated in Fig. 1b, TSS consists of external and internal cylinders, defined by diameter and thickness, with an infill of spokes arranged in a triangular pattern, characterized by their number and thickness. Here, an optimized TSS is presented, featuring an external cylinder with a diameter of 1412 mm and a thickness of 6 mm, an internal cylinder with a diameter of 748 mm and a thickness of 2 mm, and 22 spokes, each with a thickness of 2 mm. This TSS configuration results from a blended design approach, as proposed in [11], integrating structural design principles, generative design algorithms and WAAM manufacturing constraints [12]. The feasibility of fabricating this configuration using WAAM was demonstrated with a first prototype presented in [3]. Consequently, as a preliminary assumption, this paper focuses on the manufacturing process used for that prototype, even though a TSS with different geometrical parameters is now considered.
The functional unit is defined as a tubular element with a length of 2 m, an external diameter of 1412 mm and equivalent radial pressure capacity. Since both CHS and TSS fulfil the same functional requirements, a direct comparison between the products relevant to industrial applications is enabled.

(a) (b)

Figure 1. Geometrical configuration and parameters of (a) CHS and (b) TSS

2.2. System boundaries

The environmental impact was assessed for the two models presented: the conventionally manufactured cold formed structural steel CHS and the WAAM steel TSS. The systems boundaries encompass processes from raw material extraction to element production, representing a “cradle-to-gate” analysis. Two production systems were considered, as illustrated in Fig.2. Specifically, the production of steel CHS involves raw material extraction, transportation to the manufacturing site for steel production and cold forming of the final CHS. While the production of WAAM steel TSS includes the same steps of raw material extraction, transportation and steel production, followed by hot-rolling to produce wire rods, transportation to the wire producer for wire drawing to produce wire tailored for WAAM, and further transportation to the WAAM facility for printing.

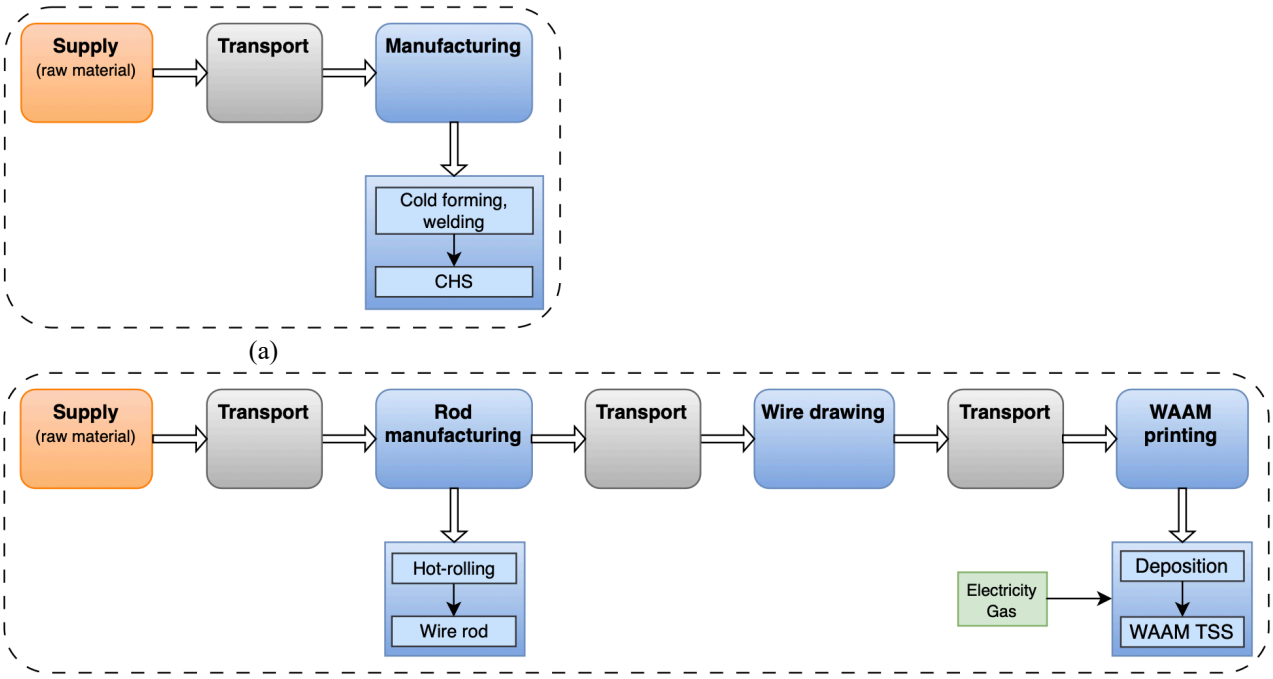


Figure 2. System boundaries considered in the production of (a) structural steel CHS and (b) WAAM steel TSS

2.3. Modelling approach

The "cradle-to-gate" analysis was conducted using several sources. Building Transparency provided the Environmental Product Declaration (EPD) associated with the production of structural steel cold formed CHS [13]. The sustainability report provided by the manufacturers supplied data regarding the environmental impact of welding wire production [14,15]. Granta EduPack 2023 R2 was used to obtain data on carbon emissions associated with transport modes (e.g. truck > 32t EURO4 and train) and material utilization fractions in different production processes [16]. Technical sheets and online sources provided data for assessing energy consumption.

2.3.1. Production of Cold formed CHS

The production of structural steel cold formed CHS involves several key stages, including raw material supply, transportation, and manufacturing (FIG2a). The process begins with the extraction and processing of raw materials, such as steel scrap, limestone, and ferroalloys, which are essential for steel production and are delivered to the manufacturing site for further processing. The production of structural steel cold formed CHS involves shaping steel coils, which are first slit into strips of the required width. These strips are then progressively formed into circular sections through a series of cold-rolling operations at room temperature. The edges of the formed strip are welded together using high-frequency induction welding to create a continuous tube. Further rolling adjusts the final shape and dimensions. The process involves inputs like raw materials, electricity for welding and machinery, and transportation fuels. The outputs include the finished CHS, along with waste materials like trimming offcuts, potential scrap, and emissions resulting from energy consumption and transportation. Material losses are accounted for in the EPD provided, so no further considerations are needed in this CHS production analysis [13]. The EPD takes into account all the stages of CHS production, referring to a "cradle-to-gate" analysis, considering input values referred to their energy mix, raw materials and machinery up to date. The analysis considers CHS producers across different continents, reflecting various potential suppliers.

2.3.2. Production of WAAM TSS

As mentioned in Section 2.1, this study focuses on WAAM printing conducted at the AITIIP facility in Zaragoza, Spain, considering the set-up and printing parameters used for manufacturing the initial prototypes of WAAM TSS (Fig. 3) [17]. These prototypes were manufactured using steel welding wire ER70S-6 Ultramag by Lincoln Electric, with the following set-up: welding machine and torch, Fronius TPS 400i and WF 60i ROBACTA DRIVE CMT, respectively, Yaskawa GP50 robotic arm, SanArcC8 as shielding gas by Nippon Gases [18–20]. The production of WAAM TSS involves several key stages, including raw material supply, transportation, manufacturing of wire rods, wire drawing and WAAM printing (FIG2b). The process involves inputs such as raw materials, gas and electricity. Outputs include the printed TSS, along with waste materials like trimming scrap, welding spatter and cut wire, as well as emissions from electricity and transportation. The subplate on which the steel welding material is deposited is not considered in the analysis because it is reused for the next depositions.

Data on the production of shielding gas and welding wire were obtained from sustainability reports and technical sheets were available, or directly from the company. The welding wire and shielding gas are manufactured in a production site

and then transported to AITIIP Centro Tecnologico for TSS production. Therefore, emission factors of 0.11 kgCO_2eq per ton per kilometer for truck transport and 0.042 kgCO_2eq per ton per kilometer for train transport were assumed [16]. The production of welding wire involves, firstly, the production of wire rods through hot-rolling and forming obtaining a rod with a diameter of 5.5 mm. Secondly, in a different facility, during cold drawing, the wire rods are pulled through progressively smaller dies reaching a wire diameter of 1.2 mm, ready to be used as welding wire. The adopted shielding gas consists of 92% argon (Ar) and 8% carbon dioxide (CO_2). Firstly, argon is separated from air through cryogenic distillation, while carbon dioxide is captured as its byproduct. Secondly, the gases are purified and then mixed in the specified ratios. Finally, the steel gas cylinder is filled with the Ar-CO_2 mixture under high pressure. The gas cylinders are refillable with an economic life of 25 years [18].
Data on the energy consumption of the welding machine and robotic arm were calculated by referencing the printing parameters and technical sheets, then converting to emission factors based on the European carbon intensity of energy production, assumed to be 0.17 kgCO_2eq/kWh, reflecting a European energy mix of 39% fossil fuels, 22% nuclear and 39% renewables [21]. The energy consumed by the welding process per kg of printed material at a deposition rate of 4 kg/h was 2.31 kWh, while the one associated with the robot movement was 2.02 kWh per kg of printed material.
Material losses need to be considered across these multi-step processes to accurately track the amount of material carried forward at each production stage. In the TSS production, material losses have been considered during hot-rolling, wire drawing and WAAM printing, where they occur. A material utilization rate of 0.95 was assigned to hot rolling, based on the average value reported in Granta. For wire drawing, a utilization rate of 0.90 was applied, as assumed in [10]. WAAM welding was given a material utilization rate of 0.99 to account for losses due to welding spatter and cut wire [4,10]. Therefore, 1.18 kg of steel is needed to manufacture 1 kg of WAAM product.
Table 1 reports the key WAAM printing parameters adopted, which are referred to in the analysis to evaluate the total impact of the production. For further details refer to [3].

Printing parameters		
Wire feed rate	7.5	m/min
Deposition rate	4.0	kg/h
Current	238	A
Voltage	16.3	V
Gas flow rate	15	l/min

Table 1. Key WAAM printing parameters by AITIIP Centro Tecnologico [17]

Figure 3. WAAM steel TSS manufactured by AITIIP Centro Tecnologico [3,17]

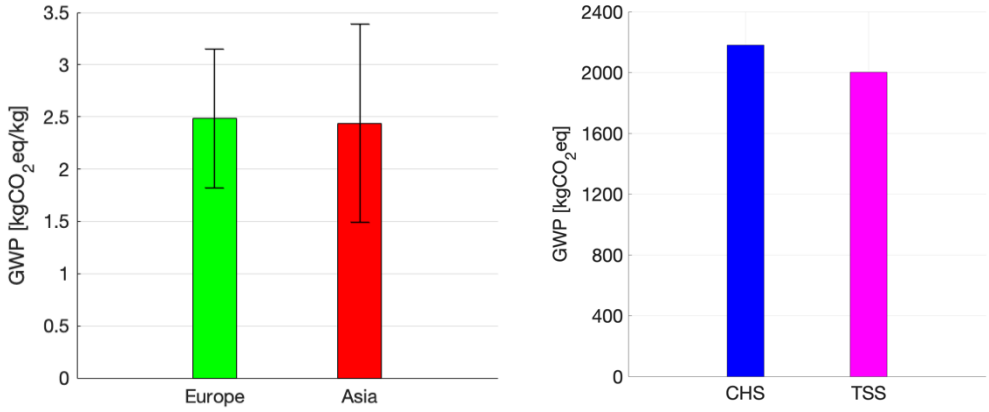
2.4. Comparative LCA

The Life Cycle Assessment (LCA) of the two products, conventional CHS and optimized WAAM TSS, was conducted to present the initial results on their environmental impact in terms of Global Warming Potential (GWP), expressed as CO_2eq. The impact of CHS production was evaluated using data from different countries to account for potential variations from different producers and to assess the average impact across continents. Specifically, Europe and Asia are referenced, based on EPDs made available by the producers. An average value from these regions is used for the comparative assessment. The impact of WAAM TSS was assessed using data specific to the gas, wire, welding and robotic equipment, as detailed in Section 2.3.2.

3. Results

The carbon footprint associated with the production of CHS and TSS has been calculated and expressed in CO_2eq. The value for CHS was determined using data from six European producers and three Asian producers, based on the available EPDs. Fig. 4a shows the average GWP associated with CHS production in Europe and Asia (2.48 ± 0.67 kgCO_2eq/kg and

2.44 ± 0.95 $kgCO_2eq/kg$ respectively), highlighting a comparable average value but greater variability in the Asian data, partly due to the smaller sample size. The GWP calculation for CHS used an average of the European and Asian values, resulting in a carbon factor of 2.46 $kgCO_2eq$ per kg of CHS.
For WAAM TSS, the carbon footprint was computed as the sum of several steps, including wire and gas production, their transport to the AITIIP facility, and the energy consumption involved in the WAAM printing step. This includes the energy used by the welding machine, robotic arm, and an additional 10% to account for ventilation, heating, lighting, and office energy consumption at the facility. Specifically, the wire rod carbon factor is 1.50 $kgCO_2eq$ per kg of wire rod, reflecting a 50% allocation to each route (such as blast furnace and direct-reduction with electric arc furnace) based on the CO_2-emission targets stated in the company report [14]. The welding wire carbon factor, associated with wire drawing, is 0.08 $kgCO_2eq$ per kg of welding wire [15]. The carbon factor for the Ar-CO_2 mixture is 0.021 $kgCO_2eq$ per gas cylinder [22]. The carbon factor associated with WAAM, considering welding machine and robotic arm, is 0.64 $kgCO_2eq$ per kg of WAAM TSS, with an additional 10%. Fig. 4b shows a bar chart with the carbon footprint of both CHS production and WAAM TSS production, highlighting the reduced impact of the novel production. Table 2 presents the emission factors for each step of the WAAM TSS production, normalized per kg of WAAM TSS, and reports the total impact for both products based on their mass, with values of 2181 $kgCO_2eq$ for CHS and 2003 $kgCO_2eq$ for WAAM TSS.



(a) (b)

Figure 4. (a) GWP associated with CHS production in Europe and Asia (expressed in $kgCO_2eq/kg$); (b) GWP comparison between average CHS and WAAM TSS production expressed in $kgCO_2eq$.

	Unit	Cold formed CHS	WAAM TSS
Mass			
Final product	kg	886	735
Emission factor			
CHS production	$kgCO_2eq/kg_{CHS}$	2.46	
Wire production	$kgCO_2eq/kg_{TSS}$	-	1.818
Gas production	$kgCO_2eq/kg_{TSS}$	-	0.001
Transportation	$kgCO_2eq/kg_{TSS}$	-	0.180
WAAM	$kgCO_2eq/kg_{TSS}$	-	0.709
Total impact			
CHS production	$kgCO_2eq/kg_{CHS}$	2.46	-
TSS production	$kgCO_2eq/kg_{TSS}$	-	2.73
Product	$kgCO_2eq$	2181	2003

Table 2. Mass, emission factors and total impact for cold formed CHS and WAAM TSS.

4. Conclusions

A notable result is WAAM's capability to produce complex geometries like the TSS, enabling optimized designs that reduce component mass while maintaining the same mechanical performance. The TSS achieves a 17% mass reduction compared to the conventional CHS. Readers interested in more details on how to design an optimized TSS can refer to [3]. The results show an increase in the carbon footprint when comparing CHS and WAAM TSS production, rising from 2.46 $kgCO_2eq/kg_{CHS}$ to 2.73 $kgCO_2eq/kg_{TSS}$, representing an 11% increase. However, this increase is normalized for the specific production process. When considering the mass reduction of the WAAM steel TSS, it results in an 8% decrease in $kgCO_2eq$ per unit of the produced structural element. This demonstrates a carbon footprint advantage associated with the WAAM technology, which allows for the creation of complex optimized sections.
In WAAM TSS production, the largest impact is associated with wire production. Consequently, improvements in wire rod production, aimed at meeting CO2-emission targets, which are already being pursued by the producer reported in this

paper, will contribute to further reducing the carbon footprint of WAAM production [14]. It will be a focus of future developments.

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