

# A Comparative Life Cycle Assessment of Structural Solutions Using Dissimilar Materials and Hybrid Joints

Francesca DI CAROLO<sup>a,1</sup>, Pratap Kumar JOHN<sup>a</sup>, Rosa DE FINIS<sup>b</sup>, Davide PALUMBO<sup>a</sup>, Ester D'ACCARDI<sup>a</sup>, Vincenzo CRUPI<sup>c</sup>, Giovanni BRIGUGLIO<sup>c</sup> and Umberto GALIETTI<sup>a</sup>.

<sup>a</sup>Poltechnic University of Bari, Via Edoardo Orabona, 4, 70126 Bari, BA, Italy

<sup>b</sup>University of Salento, Piazza Tancredi, n7, 73100 Lecce, LE, Italy

<sup>c</sup>University of Messina, Contrada Di Dio - Vill. Sant'Agata, 98166, Messina, ME, Italy

ORCID ID: Francesca Di Carolo <https://orcid.org/0000-0001-5222-0564>

**Abstract.** In this work, a Life Cycle approach is implemented to compare the environmental performances of innovative technologies such as dissimilar joints, hybrid metal-composite joints, and additive manufactured (AM) components. The study is part of a broader project whose goal is to develop solutions that improve the performance and durability of components and reduce their environmental impact throughout the life cycle, promoting circular economy principles, recyclability, and the production of sustainable structures. For dissimilar joints, the use of AM is particularly promising as it can improve the sustainability and circularity of manufacturing processes. AM has already shown great potential, though significant work is needed to meet the performance standards of the industry. In the case of hybrid joints, the goal is to combine different materials to create stronger, more durable composites that can improve the reliability of structural ship details. This approach supports the circularity of the shipyards supply chain, which is increasingly focused on lightweight materials to boost efficiency and reduce carbon emissions. The main objective of the study is to establish a robust basis for decision making and guide the design of components that must perform well both in terms of mechanical properties and environmental performance. The scenarios to be compared concern components fulfilling the same structural function, but produced using different materials and joining techniques; specifically, scenarios will include cases with traditional materials (e.g., welded steel joints), cases with dissimilar joints realized using different innovative techniques, with base materials manufactured through various processes (including additive manufacturing), and hybrid components.

**Keywords:** LCA, Hybrid Joints, Dissimilar Joints, Explosion Welding, Friction Stir Welding.

## 1. Introduction

Ship design focused on environmental sustainability has become a topic of significant interest and seen substantial development in recent years. This growth is driven by both increased environmental awareness, fostering a desire to protect future generations, and

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<sup>1</sup> Corresponding Author: Francesca Di Carolo, [francesca.dicarolo@poliba.it](mailto:francesca.dicarolo@poliba.it)

actions from legislators and regulators [1]. Designers have access to various tools, including guidelines, strategies, and analysis methods, to identify and select the most eco-efficient design options. Life Cycle Assessment (LCA) is undoubtedly the best approach for this purpose [2], while the design direction is clearly towards increasingly lighter structures that optimize the strength-to-weight ratio. Lightness translates directly into lower resource consumption and reduced energy absorption, and from a life cycle perspective, this significantly reduces impacts across all phases – from resource acquisition and production through useful life and disposal. In the naval sector, however, the challenging environmental conditions necessitate finding materials that balance lightness, mechanical strength, and corrosion resistance. Hybrid solutions and dissimilar joints represent an optimal approach to this challenge, leveraging the strengths of different materials to ensure both lightness and durability [3-5].

Focused on the Life Cycle Inventory (LCI) comparison of three different welding solutions for a ship balcony component, this work is part of a broader project applying a complete Life Cycle Assessment – from material production to disposal – to compare the environmental sustainability of solutions that improve the performance and durability of components, specifically those utilizing hybrid and dissimilar joints.

The study concerns a preliminary LCA, and the results are related only to the inventory of the welding processes, in terms of resource flows, energy, emissions, products, and waste.

## 2. Balcony Supporting Frame

To compare the environmental performance of different joining techniques, a simple component has been chosen: a support frame for a ship balcony overhang. This component features a metal wall onto which a cantilevered panel, designed to support the weight of a person, must be mounted. Since the panel, its supporting arms, and the system for anchoring it to the steel wall need to be as lightweight as possible, the arms and fixing plates are made of aluminium. The panel itself is made of an aluminium honeycomb sandwich material. The reference component configuration includes explosion welded joints for the aluminum-to-steel connections. It also includes a bolted connection to bond the sandwich panel and the supporting plates, allowing simple substitution of the panel to be tested. This balcony frame has an estimated weight of 63 kg, significantly less than a previous reference structure, which weighed 135 kg. Figure 1 shows the experimental set-up for the full scale tests on the ship detail reported in [4].

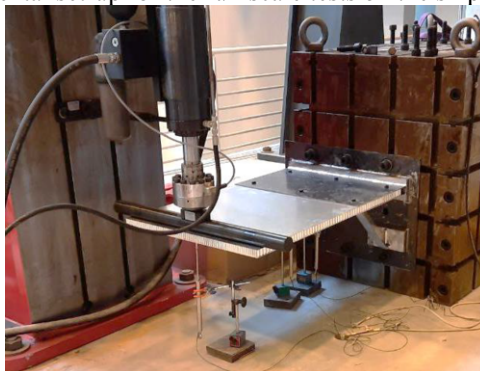


Figure 1: Experimental set-up of the ship balcony overhang.

### 3. Welding technologies parameters and assumptions

#### 3.1. Explosion Welding (EXW)

Explosion Welding is a solid-state process that works on the basic principle of metallurgical bonding. In this process, a controlled detonation of explosive is used on the welding surface. This explosion generates a high-pressure force, which deforms the work plates plastically at the interface in order to form a metallurgical bond between these plates. This metallurgical bond is stronger than the parent materials.

Advantages of the process include the capacity to join both similar and dissimilar materials, simplifying operation and handling while also being capable of welding large surfaces in a single pass. Furthermore, it provides a high metal joining rate, with the majority of the time typically allocated to preparation rather than the welding itself. A significant benefit is that the process does not negatively affect the inherent properties of the materials being welded. Finally, as a solid-state process, there is no need for filler material or flux, streamlining the procedure and potentially reducing costs. [6]:

In this study, aluminium alloys AA5086 and AA1050, along with ASTM A516 Gr55 steel, were selected for the balcony supporting frames [6-8] which consists of three welded sections with assumed lengths of 750 mm, 305 mm, and 305 mm, maintaining a uniform width of 155 mm [4]. For simplification in analysis, the total length was approximated as 1360 mm. All layers share these dimensions but differ in thickness:

- Top/Flyer plate (AA5086): 6 mm, density 2.66 g/cm<sup>3</sup>, mass 3360 g.
- Middle/Interlayer (AA1050): 9.5 mm, density 2.71 g/cm<sup>3</sup>, mass 5430 g.
- Bottom/Base plate (ASTM A516 Gr55): 19 mm, density 7.85 g/cm<sup>3</sup>, mass 31400 g.

The explosive material selected was RDX (Cyclotrimethylene Trinitramine) because of its high energy density (~5.3 MJ/kg). A total charge mass of 26620 g can deliver approximately 35.13 kWh of energy, sufficient to induce controlled jetting and effective bonding without material melting. [6, 8]. A standoff distance of 2 mm has to be to ensure proper flyer plate acceleration and controlled impact pressure, facilitating effective jet formation. This distance lies within the optimal range for solid-state bonding between aluminium and steel [6, 7]. A shockwave velocity of 2 m/s and a welding time of 0.68 s were considered to achieve interfacial bonding through plastic deformation while minimizing jetting, surface melting, or bond defects [8]. Lubricant oil (10 mL, ISO VG 68), hydraulic oil (25 mL, ISO VG 46), and lithium-based grease (4 g, NLGI 2) were selected to reduce wear in fixtures, ensure smooth operation of clamping and flyer alignment systems, and enhance process stability. The EXW process setup modelled in this study is depicted in Figure 2, which shows the arrangement and interaction of the materials during detonation.

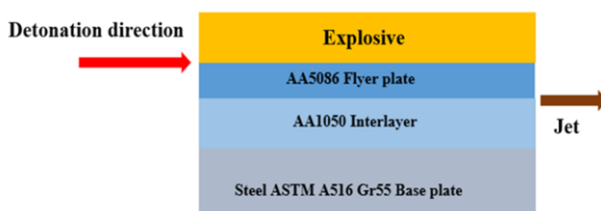


Figure 2: EXW process setup

### 3.2. Friction stir welding (FSW)

FSW is a solid-state joining process that allows joining materials that are hard to weld (like aluminum alloys and other light metals) without melting the base materials [9-11]. FSW is highly suited for dissimilar material welding, since the risk of formation of fragile intermetallic phases and metallurgical incompatibilities is very low [9-11]. It uses a rotating tool to generate heat through friction, which softens the materials and allows them to be mechanically stirred and joined together. FSW offers several advantages, including minimal waste production and no need for filler materials, shielding gases, or flux [9-11]. It also reduces the need for post-processing steps such as grinding. Furthermore, it is a relatively low-energy process compared to traditional fusion welding methods, and it guarantees the preservation of the initial mechanical properties of the materials, particularly for sensitive materials like aluminum.

In the present work, FSW was considered to fabricate the balcony supporting frames using aluminium alloy AA5086 and ASTM A516 Gr55 steel. Plates with dimensions of 1360 mm X 155 mm and 20 mm thickness were joined over a total weld length of 2.72 m [4]. A butt joint configuration was selected to ensure uniform stress distribution and effective load transfer [9, 10]. The softer aluminium alloy (2.66 g/cm<sup>3</sup>, 11200 g) was positioned on the retreating side, and the harder steel (7.85 g/cm<sup>3</sup>, 33090 g) on the advancing side to promote optimal material flow and minimize intermetallic compound (IMC) formation [9, 10]. The welding tool, made of H13 tool steel and selected for its excellent wear resistance and thermal stability, featured a plain shoulder (30 mm diameter, 60 mm length) and a cylindrical pin (10 mm diameter, 10 mm length) [9, 10]. Tool design ensured full penetration and minimized weld defects [9, 10]. The process parameters were chosen according to the literature, 600 rpm rotational speed, 45 mm/min traverse speed, 0.5 mm offset toward steel, 7 kN axial force, 10 mm plunge depth, and 2° tool tilt, in order to provide a balanced heat input and material mixing, enhancing joint strength, ductility, and fatigue performance [9, 11]. Total electricity consumption during welding was estimated 12.84 kWh. Lubricants and fluids used included servo oil (42 mL), hydraulic oil (10.5 mL, mineral-based System 68), coolant (63 mL, water-based TRIM<sup>®</sup> C270), and grease (2.4 g, lithium-based Mobilux<sup>™</sup> EP 2), ensuring thermal control, reduced tool wear, and consistent weld quality. Figure 3 displays the FSW setup to join the base plates.

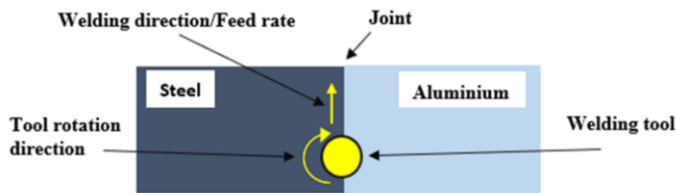


Figure 3: Setup to perform FSW

FSW was considered at the midpoint of the 20 mm plate thickness. A double-sided welding was employed to enhance structural integrity and durability. Welding from both sides improves joint symmetry and thermal distribution, resulting in more uniform stress distribution and reduced distortion compared to single-sided welds [11].

### 3.3. Metal Inert Gas (MIG) Welding

In this study, two steel plates (ASTM A516 Gr55) of the same grade, each with assumed dimensions of 1360 mm (length) X 155 mm (width) X 20 mm (thickness) with a mass of 33090 g, were considered in the joining process to make the balcony supporting frame [4]. The process consumes 0.725 kWh of energy with key welding parameters including 24 V voltage, 250 A current, 5 mm/s travel speed, welding time of 9.07 minutes, and 960 J/mm heat input. These conditions provide effective arc stability, deep penetration, and minimal spatter, ensuring strong and reliable welds [12]. The filler wire ER70S-6 (diameter: 1.2 mm, length: 13600 mm, density: 7.85 g/cm<sup>3</sup>, and mass: 120.65 g) was selected for its superior arc characteristics, weld bead quality, and deoxidizing capabilities, making it ideal for joining steels with surface impurities [12, 13]. A 90% Argon (0.001784 g/cm<sup>3</sup> and 218.36 g), 10% CO<sub>2</sub> (0.001977 g/cm<sup>3</sup> and 26.88 g), and shielding gas mix (245.24 g) enhanced arc stability and penetration, balancing quality and cost-efficiency [14]. A copper torch tip (90 g and 8.96 g/cm<sup>3</sup>) was selected for its excellent conductivity and wear resistance, ensuring stable arc control and reduced maintenance [13]. Lubricant oil (0.76 mL, Servo Way 68, ISO VG 68), Coolant (9.3 mL, Water-based, Blaser Blasocut BC 25 MD), Grease (0.73 g, Lithium-based, Mobilux™ EP 2) were considered in appropriate amounts to ensure stable and effective joint formation. Figure 4 shows the MIG welding setup to join the two base materials.

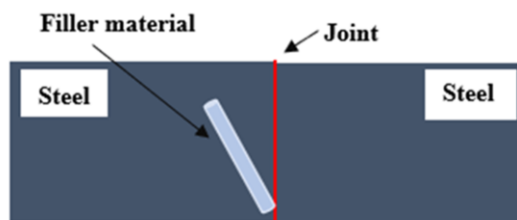


Figure 4: MIG welding procedure

The butt joint configuration was applied on both the top and bottom sides of the joint along the midpoint of the 20 mm thickness, covering a total weld length of 2.72 m. This approach ensures complete fusion and strength on both sides of the joint, providing enhanced structural integrity for the balcony supporting frame.

## 4. Life Cycle Inventory

To compare the three welding technologies, a functional unit was defined: the welding required to join the balcony frame component described in section 2. This functional unit was considered according to the configuration optimized for each specific technology. This approach corresponds to the reference flows reported in Tables 1, 2, and 3. Using these reference flows as a basis, all relevant input and output flows were then evaluated.

### 4.1. Explosion welding: Input and output flows

The outputs include the final welded component (balcony supporting frame), scrap material, emissions, and noise levels. Scrap generated of about 200.95 g,

corresponding to a scrap loss rate of 5.72 g/kWh. Explosive charge loss accounts for 2660 g, with a loss rate of 75.72 g/kWh. Emissions include fumes (104.06 g), NO<sub>x</sub> (5324 g), and CO<sub>2</sub> totaling 32092 g, largely contributed by the explosive charge (31944 g) and consumables (148 g). Noise levels during the process reach 110 dB. Chemical compounds formed during the process originate from the oxidation of base materials: AA5086 contributes oxides such as Al<sub>2</sub>O<sub>3</sub>, MgO, and MnO, totaling 3.36 g; AA1050 forms 6.5 g of Al<sub>2</sub>O<sub>3</sub>; while ASTM A516 Gr55 steel generates iron and silicon oxides totaling 94.2 g. During the EXW process, 10 mL of lubricant oil and 25 mL of hydraulic oil were utilized, with 25% of each being recycled and 75% lost. Additionally, 4 g of grease was fully consumed during the operation

**Table 1.** Life cycle inventory data (Input and output flows) for the EXW joints

INPUT FLOWS		
Flow	Notes	Quantity
Base materials		40190 g
	AA5086-	(3360 g)
	AA1050	(5430 g)
	ASTM A516 Gr5	(31400 g)
Explosive charge (RDX)	RDX	26620 g
Lubricant oil	-	10 mL
Hydraulic oil	-	25 mL
Grease	-	4 g
OUTPUT FLOWS		
Flow	Notes	Quantity
Final component	Balcony Supporting Frame	1 unit
Total scrap	0.5% (of base material mass). Scrap loss rate per unit energy: 5.72 g/kWh.	200.95 g
Explosive charge loss	Explosive charge loss rate per unit energy: 75.72 g/kWh.	2660 g
Recycled lubricant oil	25% of used amount	2.5 mL
Waste lubricant oil	75% of used amount, non-recycled	7.5 mL
Recycled hydraulic oil	25% of used amount	6.25 mL
Waste hydraulic oil	75% of used amount, non-recycled	18.75 mL
Total fume emission	Fume emission rate per unit energy: 2.96 g/kWh. Composed of:	104.06 g
AA5086 (3.23% of total fumes)	Composition: Al <sub>2</sub> O <sub>3</sub> (Aluminium oxide, 60%): 2.016 g, MgO (Magnesium oxide, 25%): 0.84 g, MnO (Manganese (II) oxide, 15%): 0.504 g.	(3.36 g)
AA1050 (6.25% of total fumes)	Composition: Al <sub>2</sub> O <sub>3</sub> (Aluminium oxide, 100%): 6.5 g.	(6.5 g)
ASTM A516 Gr55 (90.52% of total fumes)	Composition: Fe <sub>2</sub> O <sub>3</sub> (Iron (III) oxide/ferric oxide, 45%): 42.39 g, Fe <sub>3</sub> O <sub>4</sub> (Iron (II,III) oxide/magnetite, 20%): 18.84 g, FeO (Iron (II) oxide/ferrous oxide, 10%): 9.42 g, MnO (Manganese (II) oxide, 10%): 9.42 g, SiO <sub>2</sub> (Silicon dioxide, 15%): 14.13 g.	(94.2 g)
Grease (non-recycled)	Corresponds to grease used in input.	4 g
NO <sub>x</sub> emission	-	5324 g
Total CO <sub>2</sub> emission	CO <sub>2</sub> emission (explosive charge): 31944 g. CO <sub>2</sub> emission (consumables): 148 g.	32092 g
Noise levels	-	110 dB

#### 4.2. Friction stir welding: Input and output flows

For the FSW process, a total tool material loss of 7 g and 132.87 g of scrap (0.3%) were recorded, resulting in a scrap rate of 10.35 g/kWh. The process generated 6125.1 g of CO<sub>2</sub> emissions, with 5778 g attributed to energy consumption and 347.1 g from consumables. Fume emissions totaled 5.44 g, comprising oxides of aluminum, magnesium, manganese, iron, and silicon, while NO<sub>x</sub> emissions reached 6.42 g. Lubricants and hydraulic oil were each recycled at 80%, while coolant achieved a higher recycling rate of 90%. Noise levels during welding were measured at 70 dB. These controlled inputs and outputs demonstrate the process's efficiency, minimal waste generation, and strong environmental performance, supporting sustainable fabrication of structural components.

**Table 2.** LCI data (Input and output flows) for FSW joints

INPUT FLOWS		
Flow	Notes	Quantity
Final component	Balcony Supporting Frame	1 unit
Base materials	Aluminium, Steel. Total weld length: 2.72 m.	
Aluminium	-	11200 g
Steel	-	33090 g
H13 tool steel	-	340 g
Energy	-	12.84 kWh
Lubricant oil	-	42 mL
Hydraulic oil	-	10.5 mL
Coolant	-	63 mL
Grease	-	2.4 g
OUTPUT FLOWS		
Flow	Notes	Quantity
Final component	Balcony supporting frame	-
Total scrap	0.3% (of base material mass). Scrap loss rate per unit of energy: 10.35 g/kWh.	132.87 g
Tool material loss (H13 Steel)	Tool material loss per unit of energy: 0.55 g/kWh.	7 g
Recycled lubricant oil	80% of used amount	33.6 mL
Waste lubricant oil	20% of used amount, non-recycled	8.4 mL
Total fume emission	Fume emission rate per unit of energy: 0.42 g/kWh. The total fumes (5.44g) are composed as follows:	5.44 g
AA5086 (50% of base material)	Originates 2.72g of fumes with composition: Al <sub>2</sub> O <sub>3</sub> (85%): 2.31 g, MgO (10%): 0.27 g, MnO (5%): 0.14 g.	(2.72 g)
ASTM A516 Gr55 (50% of base material)	Originates 2.72g of fumes with composition: Fe <sub>2</sub> O <sub>3</sub> (40%): 1.09 g, Fe <sub>3</sub> O <sub>4</sub> (25%): 0.68 g, FeO (20%): 0.54 g, MnO (10%): 0.27 g, SiO <sub>2</sub> (5%): 0.14 g.	(2.72 g)
Recycled hydraulic oil	80% of used amount	8.4 mL
Waste hydraulic oil	20% of used amount, non-recycled	2.1 mL
NO <sub>x</sub> emission	-	6.42 g
Recycled coolant	90% of used amount	56.7 mL
Waste coolant	10% of used amount, non-recycled	6.3 mL
Total CO <sub>2</sub> emission	Breakdown: CO <sub>2</sub> from energy: 5778 g; CO <sub>2</sub> from consumables: 347.1 g.	6125.1 g
Grease (non-recycled)	Corresponds to the grease used in input.	2.4 g
Noise levels	-	70 dB

### 4.3. MIG welding: Input and output flows

The process generated 264.72 g of scrap material, with most being recoverable. Filler wire loss was minimal at 4.826 g, of which 90% was recycled. Shielding gas consumption resulted in a loss of 7.36 g, mainly Argon and a smaller portion of CO<sub>2</sub>. Fume emissions totaled 2.07 g, consisting mainly of iron oxides and manganese compounds. CO<sub>2</sub> emissions amounted to 619.18 g, originating from energy consumption, shielding gas, filler wire, and other minor consumables. NO<sub>x</sub> emissions were recorded at 0.3625 g, with noise levels measured at 90 dB. Additionally, 95% of the lubricant oil and 75% of the coolant were recovered, while the grease was non-recyclable.

**Table 3.** LCI data (Input and output flows) for MIG welded steel joints

INPUT FLOWS		
Flow	Notes	Quantity
Base materials (Steels)	Two types of steel. Total weld length: 2.72 m.	66180 g
Filler material (ER70S-6 Wire)	ER70S-6	120.65 g
Shielding gas	Argon (90%), CO <sub>2</sub> (10%)	Total: 245.24 g
	Argon	(218.36 g)
	CO <sub>2</sub>	(26.88 g)
Torch tip material (Copper)	Copper	90 g
Energy	-	0.725 kWh
Lubricant oil (used)	-	0.76 mL
Coolant (used)	-	9.3 mL
Grease (used)	-	0.73 g
OUTPUT FLOWS		
Flow	Notes	Quantity
Final component	Balcony supporting frame	1 unit
Total scrap	0.4% (of base material). Scrap loss per unit of energy: 365.13 g/kWh.	264.72 g
Filler material loss (wire)	Loss rate: 4%. Wire material loss per unit of energy: 6.656 g/kWh.	4.826 g
Recycled filler material (wire)	90% of filler material loss.	4.3434 g
Waste filler material (wire)	10% of filler material loss, non-recycled.	0.4826 g
Shielding gas loss (Argon + CO <sub>2</sub> )	Gas loss rate: 3%. Gas loss per unit of energy: 10.15 g/kWh. Argon loss: 6.55 g. CO <sub>2</sub> loss: 0.81 g.	7.36 g
Total fumes base materials	Total fume emission rate per unit of energy: 2.855 g/kWh. Fume emission rate per unit of energy: 0.855 g/kWh. The fumes (0.62g) derive from two base material sources (ASTM A516 Gr55, each 50%), each producing 0.31g of fumes with the composition: Fe <sub>2</sub> O <sub>3</sub> (40%): 0.124 g, Fe <sub>3</sub> O <sub>4</sub> (25%): 0.078 g, FeO (20%): 0.062 g, MnO (10%): 0.031 g, SiO <sub>2</sub> (5%): 0.016 g.	2.07 g (0.62 g)
filler wire	Fume emission rate per unit of energy: 2 g/kWh. Chemical compounds: Fe <sub>2</sub> O <sub>3</sub> (30%): 0.435 g, Fe <sub>3</sub> O <sub>4</sub> (20%): 0.29 g, FeO (10%): 0.145 g, MnO (15%): 0.218 g, SiO <sub>2</sub> (10%): 0.145 g, CO (7.5%): 0.109 g, CO <sub>2</sub> (7.5%): 0.109 g.	(1.45 g)
Recycled lubricant oil	95% of used amount.	0.722 mL
Waste lubricant oil	5% of used amount, non-recycled.	0.038 mL
NOx emission	-	0.3625 g
Recycled coolant	75% of used amount.	7 mL
Waste coolant	25% of used amount, non-recycled.	2.3 mL

Total CO <sub>2</sub> emission	Breakdown: from filler wire: 300 g; from shielding gas: 26.88 g; from energy: 290 g; from consumables: 2.3 g.	619.18 g
Grease (non-recycled)	Corresponds to the grease used in input.	0.73 g
Noise levels	-	90 dB

## 5. Results and discussion

The results obtained from the LCI results allow us to draw initial conclusions that will help to improve the LCA of the system under study.

Key findings include the fact that the EXW process was primarily impacted by the steel base material, contributing over 90% of total mass and oxide emissions. Aluminium alloys add minor but relevant fumes. Explosive charge usage significantly increases CO<sub>2</sub> emissions and chemical waste, raising environmental concerns. Noise levels (110 dB) necessitate worker protection. Scrap generation is low (~0.5%), indicating efficient material use. Furthermore, the FSW process showed high efficiency with a low scrap rate (0.3%) and minimal tool wear (7 g). Energy used was 12.84 kWh, producing 6125.1 g CO<sub>2</sub> mainly from electricity. Fume emissions were low (5.44 g), and noise was controlled at 70 dB. Finally, the MIG welding process resulted in efficient material usage with minimal losses. Filler wire loss was 4.826 g (90% recyclable), and shielding gas loss totaled 7.36 g. Fume emissions were low at 2.07 g, primarily iron and manganese oxides. Total CO<sub>2</sub> emissions reached 619.18 g, mainly from energy use and consumables. Scrap generation was 264.72 g, with a noise level of 90 dB.

## 6. Conclusions and future work

In this work, the LCI for the balcony frame manufacturing has been presneted. In particular, the focus has been on different options for joining a lightweight material component (such as aluminum), which functions as a balcony, to the steel wall of a ship. The considered scenarios were therefore aluminum-steel joints achieved through EXW or FSW, and steel-steel joints obtained using the traditional MIG welding technique.

The processed data led to the following conclusions:

- EXW produces high material efficiency, but elevated CO<sub>2</sub> emissions and excessive noise levels raise environmental and occupational safety concerns.
- FSW process develops low emissions, minimal scrap, and moderate energy use, confirming FSW as a clean and efficient method.
- MIG welding offers balanced material efficiency and moderate emissions, with a practical compromise between performance and environmental impact.

A key consideration is that the data applied during this phase of the LCA analysis offers limited specificity, as it originates from similar processes, various reports, and the scientific literature. As such, the inherent uncertainty of these results must be factored into their interpretation.

This study serves as the first step in an iterative analytical process. Its outcomes are intended to guide the evaluation of more suitable alternatives for final component production, which will facilitate the acquisition of higher-specificity data and ultimately refine the accuracy of the overall analysis. The next phase of this research will extend the LCI to cover material acquisition, subcomponent production, and the end-of-life

treatment of the product. Following this, an impact assessment will be carried out to identify the key impact categories. To conclude this expanded scope, the functional unit will transition from the current demonstrator component to the manufacturing of balconies for an entire ship.

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## References

- [1] M. Tadros, M. Ventura, C. Guedes Soares, Review of current regulations, available technologies, and future trends in the green shipping industry, *Ocean Engineering*, Volume 280, 2023, 114670, ISSN 0029-8018, <https://doi.org/10.1016/j.oceaneng.2023.114670>
- [2] Chatzinikolaou, Stefanos D., and Nikolaos P. Ventikos. "Applications of life cycle assessment in shipping." *2nd international symposium on naval architecture and maritime, Istanbul, Turkey*. 2014.
- [3] Kharghani, N.; Guedes Soares, C. Experimental and numerical study of hybrid steel-FRP balcony overhang of ships under shear and bending. *Mar. Struct.* 2018, 60, 15–33.
- [4] Palomba G, Corigliano P, Crupi V, Epasto G. and Guglielmino E, Static and Fatigue Full-Scale Tests on a Lightweight Ship Balcony Overhang with Al/Fe Structural Transition Joints, *J. Mar. Sci. Eng.* 2022, 10, 1382. <https://doi.org/10.3390/jmse10101382>
- [5] Ayob, F. Joining of Dissimilar Materials by Diffusion Bonding/ Diffusion Welding for Ship Application. *Marine Frontier*. 2010; 1(2): 69-73.
- [6] Sherpa BB, Kumar PD, Upadhyay A, Kumar S, Agarwal A, Tyagi S. Effect of explosive welding parameters on Al/LCS interface clad by low velocity of detonation explosive welding (LVEW) process. *Int J Adv Manuf Technol.* 2021;113:3303–3317. <https://doi.org/10.1007/s00170-021-06800-5>
- [7] Kumar P, Ghosh SK, Saravanan S, Barma JD. Effect of explosive loading ratio on microstructure and mechanical properties of Al 5052/AZ31B explosive weld composite. *JOM.* 2023;75(1):167–175. <https://doi.org/10.1007/s11837-022-05579-4>
- [8] Chu Q, Xia T, Zhao P, Zhang M, Zheng J, Yan F, Luo H. Interfacial investigation of explosion-welded Al/steel plate: the microstructure, mechanical properties and residual stresses. *Mater Sci Eng A.* 2022;833:142525. <https://doi.org/10.1016/j.msea.2021.142525>
- [9] Taban E, Gould JE, Lippold JC (2010) Dissimilar Friction Welding of 6061-T6 Aluminum and AISI 1018 Steel: Properties and Microstructural Characterization. *Materials & Design* 31:2305–2311.
- [10] Ahmed MMZ, Jouini N, Alzahrani B, Seleman MMES, Jhaheen M. Dissimilar friction stir welding of AA2024 and AISI 1018: Microstructure and mechanical properties. *Metals.* 2021;11(2):330. <https://doi.org/10.3390/met11020330>
- [11] Bergmann LA, Batistão BF, de Alcântara NG, Gargarella P, Klusemann B. Effect of rotational speed and double-sided welding in friction stir-welded dissimilar joints of aluminum alloy and steel. *Weld World.* 2022;66(9):1747–1756
- [12] Chong K, Mhd Noor EE, Amir A, Baig MF. Study on welding characteristics and parameters of gas metal arc welding for A516 Grade 70 steel with ER70S-6 and ER308LSi filler materials. *Materials.* 2024;17(21):5391.
- [13] Lostado Lorza R, Escribano García R, Martínez Calvo MÁ, Múgica Vidal R. Improvement in the design of welded joints of EN 235JR low carbon steel by multiple response surface methodology. *Metals.* 2016;6(9):205.
- [14] Teske M, Martins F. The influence of the shielding gas composition on GMA welding of ASTM A 516 steel. *Weld Int.* 2010;24(3):222–230.