Deliverable D6.3

WP6. Life Cycle Assessment

# Comparative LCA and LCC of the developed technology (F)

Stig Irving Olsen, Valentina Pusateri
Danmarks Tekniske Universitet

Delivery date 31/08/2024 (updated on 12/11/2024)

Dissemination level PU

Version 2.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862017

# Contents

# Abbreviations

| | |
|---|---|
| CM | Conventional manufacturing |
| EOL | End-of-life |
| FU | Functional unit |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| WAAM | wire arc additive manufacturing |
| MM-WAAM | multi-material wire arc additive manufacturing |
| GW | Global warming |
| SOD | Stratospheric ozone depletion |
| IR | Ionizing radiation |
| OF, HH | Ozone formation, Human health |
| FPMF | Fine particulate matter formation |
| OF, TE | Ozone formation, Terrestrial ecosystems |
| TA | Terrestrial acidification |
| FEU | Freshwater eutrophication |
| MEU | Marine eutrophication |
| TE | Terrestrial ecotoxicity |
| FCE | Freshwater ecotoxicity |
| MEC | Marine ecotoxicity |
| HCT | Human carcinogenic toxicity |
| HNCT | Human non-carcinogenic toxicity |
| LU | Land use |
| MRS | Mineral resource scarcity |
| FRS | Fossil resource scarcity |
| WC | Water consumption |

# Executive summary

This deliverable consists of the final reporting of Life Cycle Assessment (LCA) and financial Life Cycle Costing (LCC) for all Grade2XL demonstrators. The purpose of this deliverable is to obtain a comparative assessment of the same products fabricated with conventional manufacturing and wire arc additive manufacturing (WAAM) to find ways to optimize the environmental and economic impact of the latter. The demonstrators considered are: A-1 (ship propeller), A-2b (holding ring for hydroelectric power plants), B-1 (bathtub mould), B-2 (mandrel tool for aerospace parts), B-3b (injection mould for optical fiber closure), B-4.1 (cutting tool automotive parts), B-4.2 (forming tool automotive parts), B-5 (forming die for washing machine drum) and B-6 (repair of a forging die for automotive parts). The LCAs were based on the ILCD guidelines and the standard ISO14040/44[1], SimaPro 9.6.0.1 software and ecoinvent 3.9.1 database were used to model the life cycle assessment of the Grade2XL demonstrators.

So far, products manufactured with WAAM, in general, performed environmentally and economically better than conventional manufacturing. Moreover, some metals, e.g. Nickel, have high impact on abiotic resource depletion. It was possible to notice a reduction of environmental impact whenever product redesign with functional grading, made feasible through multi-material WAAM, was applied. For instance, the GKN´s mandrel tool (B-2) showed increased resource use efficiency thanks to design inspired by topology optimization; and Shapers´s injection mould (B-3b) illustrated that a reduction of energy demand due to more-complex shape of cooling channels has positive effects on the total impact score. Generally, products produced with conventional manufacturing had as main source of impact the feedstock production, while when WAAM was used the main source of impact were feedstock production or manufacturing (e.g., for B-3b is the casted iron frame), or WAAM energy for the Ionizing radiation category. Production costs for WAAM are generally lower than the conventional manufacturing option, except for some demonstrators (i.e. A-1, B-5). WAAM also has the potential to reduce the lead time from 31% up to 92%, compared to conventional options.

# 1 Introduction to LCA and LCC

The main objectives for **deliverable D6.3** are:

- To gather life cycle environmental and economic data for current practice and Wire Arc Additive Manufacturing by using: existing data, database and collecting data from industrial partners. Generally, primary data from the companies involved in the Grade2XL project was the preferred option;
- To verify if the "Goal and scope" defined at the initial stage of the study is still in line with the current aim of the analysis;
- Identify processes and materials with relatively high environmental impact and/or cost;

In particular, in regards to the **Life Cycle Assessment (LCA):**

- It is a comparative assessment and hot-spots analysis at the same time;
- It is from cradle-to-grave (with possible exclusion of processes/life cycle stages in case they are the same for the alternatives);
- It includes: functional unit, reference flow, system boundaries, life cycle inventory (LCI), characterized results for midpoint impact categories (LCIA method ReCiPe2016 (H)-World), process contribution analysis, sensitivity and uncertainty analysis. In particular, the sensitivity analysis regarded best and worst scenarios of each products manufactured with WAAM. In this way, several uncertain parameters and processes were modified at same time to verify to what extent the results would change. To evaluate the uncertainties in life cycle inventories for foreground processes, we used the pedigree matrix, which allowed us to calculate the geometric standard deviation of the data points, assuming a log-normal distribution. This method enabled us to perform a Monte Carlo simulation with 1,000 iterations using SimaPro software. Specifically, the geometric standard deviation was calculated as follows:

$$\sigma_g^2 = \exp\left(\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_b)]^2}\right) \quad \text{(eq. 1)}$$

  Where, $\sigma_g^2$ represents the squared geometric standard deviation (variance, 95% confidence interval). The terms $U_1 - U_5$ denote the uncertainty factors related to reliability, completeness, temporal correlation, geographic correlation, and future technological developments. Additionally, $U_b$ represents the basic uncertainty factor. To derive the values of those factors the Pedigree matrix was used [3].
- The LCA software and database used are SimaPro 9.6.0.1, and ecoinvent 3.9.1, respectively;
- Characterized results of all demonstrators with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology were included;
- The conceptual framework for the step-by-step LCA procedure is illustrated below (see Figure 1).

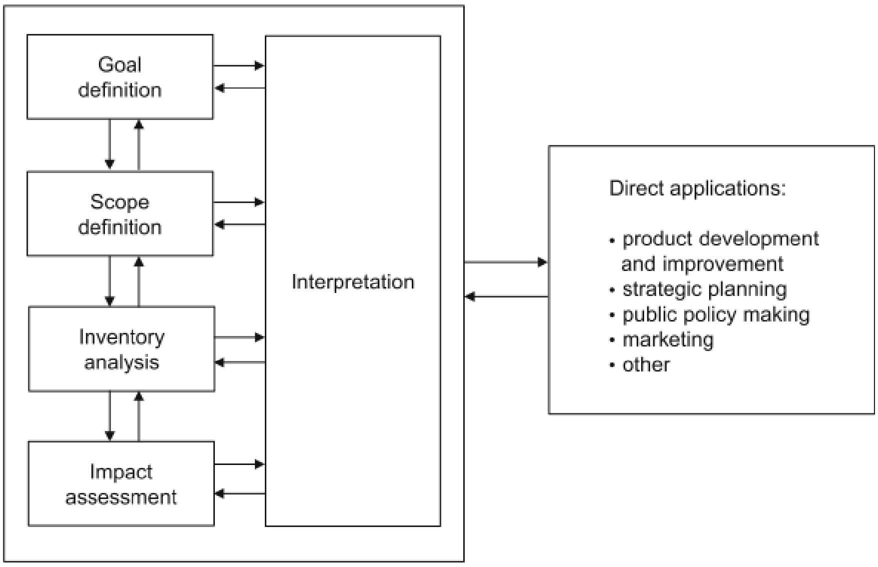



**Figure 1.** *Conceptual framework LCA [1].*

For what concerns the **Life Cycle Costing (LCC):**

- It is a comparative assessment, and it is from cradle-to-grave (with possible exclusion of processes/life cycle stages in case they are the same for the alternatives);
- The environmental life cycle costing (eLCC) is now focusing on a financial life cycle costing (see Figure 2), and estimates of the main costs and revenues of each demonstrator produced whether with conventional or wire arc additive manufacturing (see Figure 3);
- Depending on the market projections and the stakeholder involved for the end-user products, this assessment might be redundant and repetitive if the scenarios identified for the products are similar.

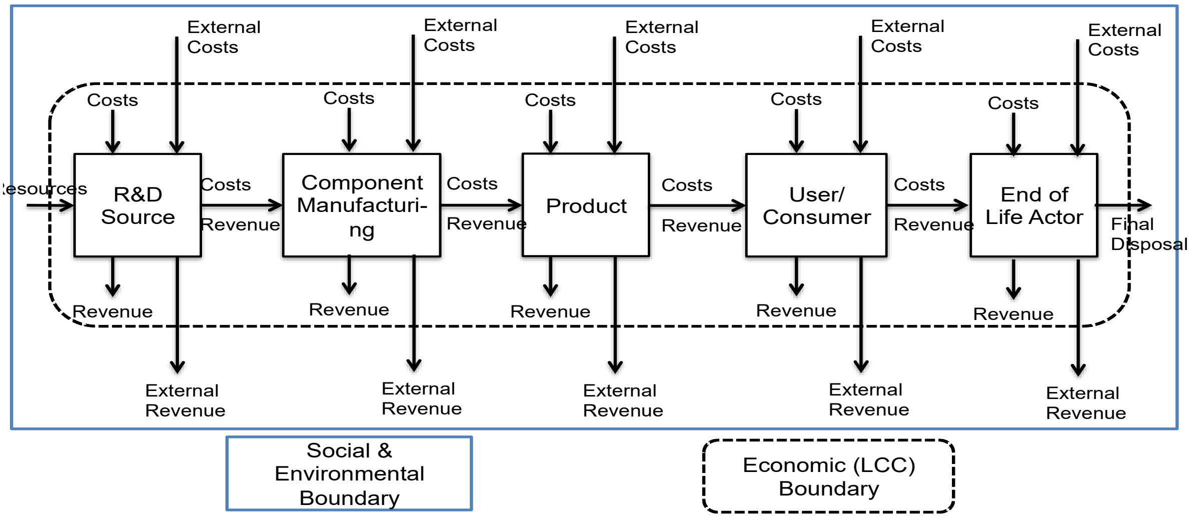



**Figure 2.** *Conceptual framework for Life Cycle Costing (LCC) from [2].*

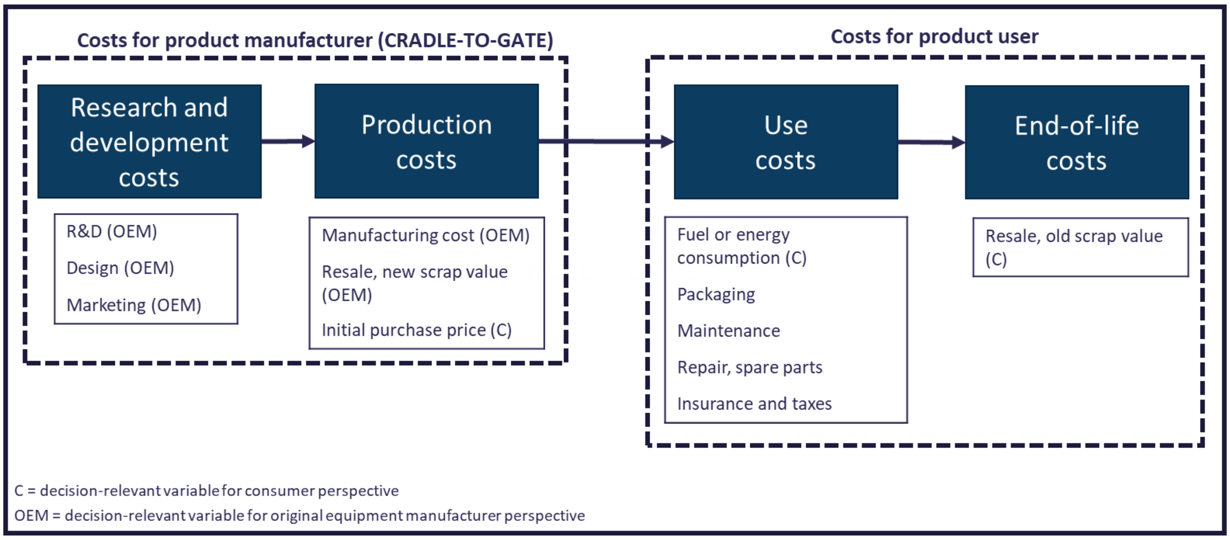


**Figure 3.** *Life Cycle Costing for product (CRADLE-TO-GRAVE). Adapted from [3].*

# 2 Goal and scope

This section illustrates the results of the final LCA and LCC assessment. The results are reported separately for each of 9 Grade2XL demonstrators. In addition to that, two summary tables, one for the functional unit and reference flow, and another one for the first iteration conclusion were included at the beginning and at the end of this section. Then for each demonstrator the most relevant parts of the assessment are represented:

- system boundaries, which in a LCA defines which processes of the studied product system are included in order to achieve the required degree of completeness in the product system modelling [1]. They can be distinguished in foreground and background boundaries. The former includes the processes of the product system that the commissioner of the study can influence (e.g. production of the injection mould with 3D printing). Usually the foreground system is created using primary data, i.e. data collected first-hand by the LCA practitioner. The background boundaries comprises all the processes which take part in numerous product systems besides the one studied, e.g. electricity production [1];
- characterized results is a mandatory step of the impact assessment stage of LCA [1], in this study calculated with ReCiPe 2016 (H). The substances that contribute to an impact category are multiplied by a characterization factor that expresses the relative contribution of the substance. For example, the characterization factor for $CO_2$ in the Climate change impact category is equal to 1, while the characterization factor of methane can be 25. This means the release of 1 kg methane causes the same amount of climate change as 25 kg $CO_2$. The total result is expressed as impact category indicators (formerly characterization results);
- interpretation of results including process contribution analysis and scenario sensitivity analysis (best and worst scenario of WAAM). Particularly the process contribution analysis for demonstrators manufactured with WAAM consists of:
    - *wire production*, which includes unit processes for wire production and alloy production;
    - *shielding gas* that includes unit processes for gasses production and consumption;
    - *welding fumes*, which includes unit process for air emissions from wire use;
    - *WAAM energy* that includes only the energy consumption for active deposition with WAAM;

- *manufacturing* that includes transportation, scrap production, milling or post-treatment processes, and if it is a hybrid manufacturing process as for B-3b that involves also a cast iron frame, this is included in the manufacturing;
    - *disposal*, which includes recycling of the metallic products when they can no longer be used or repaired and crediting is considered.
- product life cycle cost inventories and the related graphs depicting the differences between the conventional manufacturing and the WAAM option.

Finally, in Appendix A and B the assumptions and related justifications were listed for each Grade2XL demonstrator, as well as the life cycle inventory of unit processes, costs and revenues for each demonstrator.

In order to develop a fair comparative LCA of alternative ways of fabricating Grade2XL demonstrators it is necessary to define a functional unit (FU). This states both the qualitative and quantitative aspects of the alternatives considered in the comparison. In particular, the formulation of the FU need to consider some questions: “what?”, “how much?”, “for how long/how many times?”, “where” and “how well?” [1]. Moreover, the reference flow expresses the amount of product needed to fulfill the functional unit [1], and usually this was the final weight of the finished demonstrator.

Table 1 shows an overview of the functional units and reference flows used for each Grade2XL demonstrator.

**Table 1.** *Functional unit and reference flow of Grade2XL demonstrators. (* is for 46% lifetime extension for WAAM ship propellers, based on hardness increase (205/140=1.46); thus instead of 20 years is ~29 years; ** confidential data).*

| Demonstrator | Company | Product | Functional unit | Reference flow (kg) | |
|---|---|---|---|---|---|
| | | | | CM | WAAM |
| A-1 | MAN | Ship propeller (small) | *Enabling the transportation of a fully loaded commercial ship for 5,520,000 km* | 551 | 447* |
| | | Ship propeller (medium) | | 9462 | 7294* |
| | | Ship propeller (large) | | 19905 | 14972* |
| A-2b | EDF | Holding Ring (hydroelectric) | *Enabling the production of XX GWh** for 40 years in France* | 300 | 300 |
| B-1 | Villeroy & Boch | Bathtub Mould showface (white goods) | *Enabling the production of 10,000 methyl methacrylate bathtubs without surface defects in the Netherlands* | 2548 | 972 |
| B-2 | GKN | Mandrell tool (aerospace) | *Enabling the production of 100 aerospatial composites a year for 20 consecutive years in the UK* | 484 | 176 |
| B-3b | Shapers | Injection Mould (optical fiber closure) | *Enabling the production of 1 million thermoplastic parts of optical fiber closure for 17 consecutive years in France* | 3376 | 1479 |
| B-4.1 | Gorenje | Cutting tool (automotive) | *Enabling the production of 100,000 pieces of metallic automotive parts for 7 consecutive years in Slovenia* | 9.5 | 14 |
| B-4.2 | | Forming tool (automotive) | *Enabling the production of 100,000 pieces of metallic automotive parts for 7 consecutive years in Slovenia* | 61.2 | 67 |

| | | | | | |
|---|---|---|---|---|---|
| B-5 | | Forming die (washing machine drums) | *Enabling the production of 100,000 pieces of back of washing machine drums for 5 consecutive years in Slovenia* | 87.6 | 90 |
| B-6 | Kuznia Jawor | Forging die (repair case) | *Repair of forging die enabling production of 2500 pieces of lifting tool for automotive parts for 2 consecutive years in Poland* | 192 | 66.4 |

# 3 LCA and LCC results

## 3.1. Demonstrator A-1

This demonstrator is a ship propeller that comes in three different sizes small, medium, and large. It is produced by MAN ES for use in medium fishing vessels or cargo ships, depending on the ship propeller size. Wire Arc Additive Manufacturing (WAAM) will be used for its components production: blade, hub, and hub cylinder. Each propeller was assumed to have 4 blades in total. With WAAM a potential 0.1% propulsive efficiency increase (due to reduction of cavitation erosion damage) and increase in product lifetime of roughly 46% was estimated.
The lead time with WAAM was estimated to be potentially reduced from 84 weeks to 18 – 54 weeks, thus from 36% to 79%.

### 3.1.1 Life Cycle Assessment (LCA)

A)

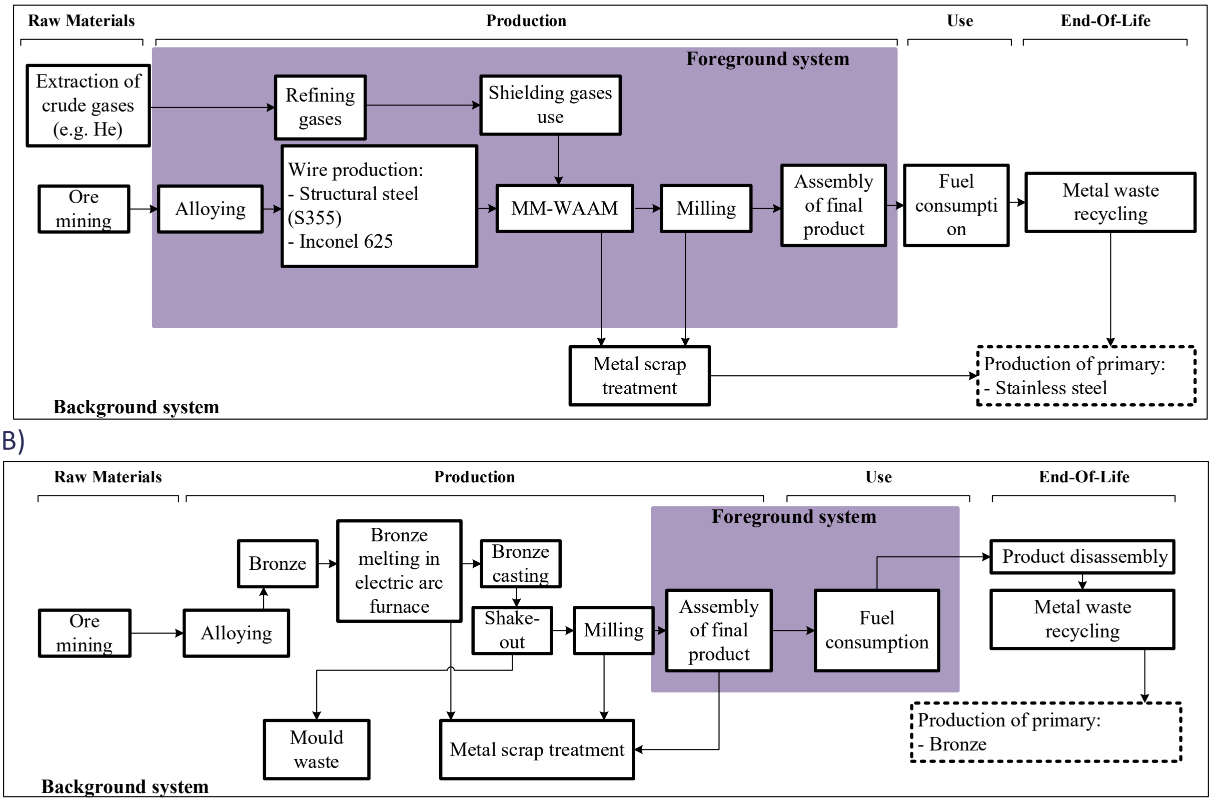



**Figure 4.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured MAN ship propeller. Note: MM-WAAM = multi-material wire arc additive manufacturing.*

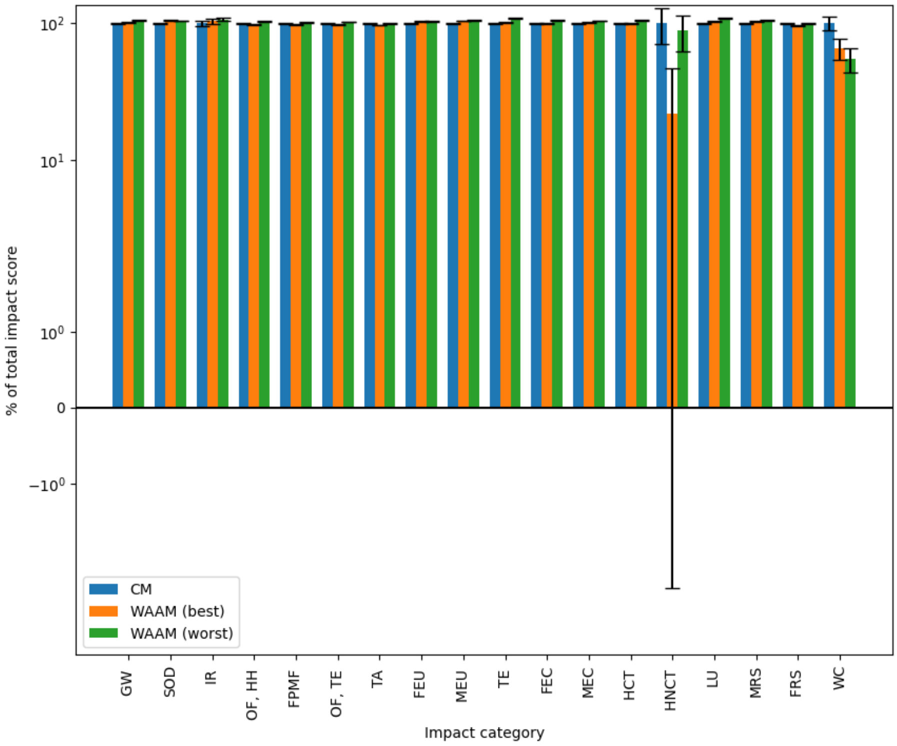
**Table 2.** *Summary of scenario sensitivity analysis of MAN ship propeller. Note that data and assumptions are based on the last meeting with the project partners on 24 - 09 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized shielding gas flow (15 L/min)<br>• Specific energy consumption low | • Current shielding gas flow (20 L/min)<br>• Specific energy consumption high |
| Use stage | | • 0.1% propulsive efficiency increase (due to reduction of cavitation erosion damage)<br>• increase in product lifetime of roughly 46%. | • No propulsive efficiency improvements in comparison to CM<br>• increase in product lifetime of roughly 25% less than 46%. |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

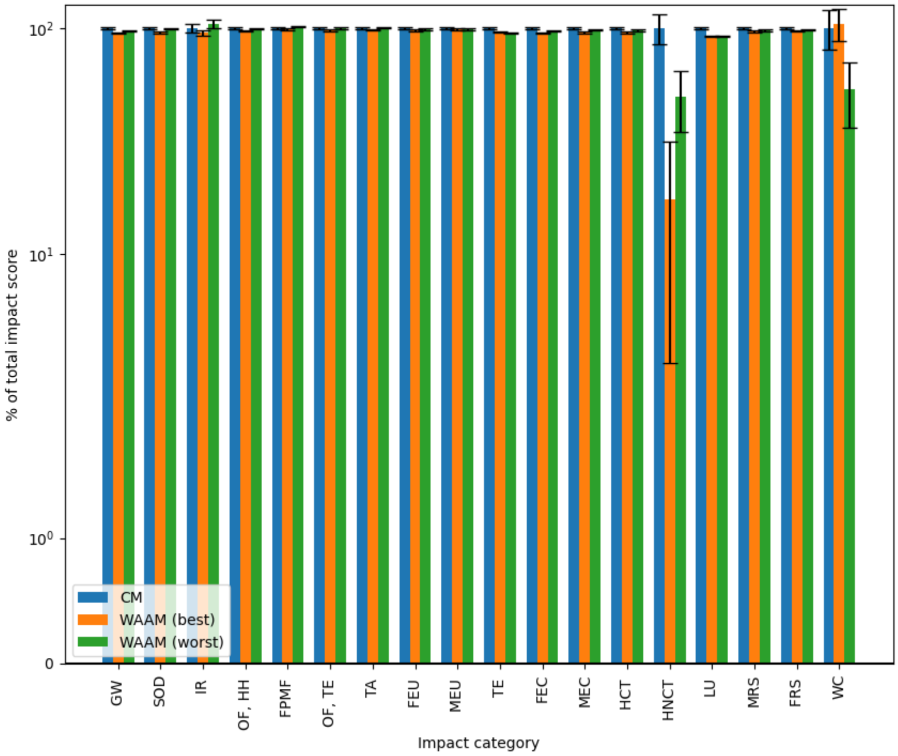
**Table 3.** *Characterized results for demonstrator A-1 (small, medium and large ship propeller) ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | Small ship propeller | | | Medium ship propeller | | | Large ship propeller | | |
|---|---|---|---|---|---|---|---|---|---|
| | CM | WAAM (best) | WAAM (worst) | CM | WAAM (best) | WAAM (worst) | CM | WAAM (best) | WAAM (worst) |
| GW [kg CO2 eq] | 6.05E+09 | 6.13E+09 | 6.35E+09 | 6.36E+09 | 6.07E+09 | 6.17E+09 | 6.00E+09 | 6.04E+09 | 6.28E+09 |
| SOD [kg CFC11 eq] | 4.27E+03 | 4.49E+03 | 4.47E+03 | 4.63E+03 | 4.43E+03 | 4.59E+03 | 4.29E+03 | 4.36E+03 | 4.62E+03 |
| IR [kBq Co-60 eq] | 7.14E+07 | 7.42E+07 | 7.63E+07 | 7.43E+07 | 7.10E+07 | 7.76E+07 | 7.62E+07 | 7.24E+07 | 8.34E+07 |
| OF, HH [kg NOx eq] | 6.28E+07 | 6.15E+07 | 6.48E+07 | 6.33E+07 | 6.17E+07 | 6.30E+07 | 6.24E+07 | 6.10E+07 | 6.51E+07 |
| FPMF [kg PM2.5 eq] | 1.07E+07 | 1.05E+07 | 1.09E+07 | 1.07E+07 | 1.06E+07 | 1.09E+07 | 1.04E+07 | 1.04E+07 | 1.11E+07 |
| OF, TE [kg NOx eq] | 6.41E+07 | 6.26E+07 | 6.59E+07 | 6.43E+07 | 6.30E+07 | 6.44E+07 | 6.35E+07 | 6.24E+07 | 6.66E+07 |
| TA [kg SO2 eq] | 2.83E+07 | 2.76E+07 | 2.85E+07 | 2.84E+07 | 2.79E+07 | 2.87E+07 | 2.76E+07 | 2.77E+07 | 2.96E+07 |
| FEU [kg P eq] | 4.88E+05 | 5.07E+05 | 5.08E+05 | 5.22E+05 | 5.11E+05 | 5.16E+05 | 5.14E+05 | 5.07E+05 | 5.39E+05 |
| MEU [kg N eq] | 1.32E+05 | 1.38E+05 | 1.39E+05 | 1.38E+05 | 1.36E+05 | 1.36E+05 | 1.31E+05 | 1.33E+05 | 1.40E+05 |
| TE [kg 1,4-DCB] | 9.56E+09 | 9.67E+09 | 1.04E+10 | 1.02E+10 | 9.87E+09 | 9.73E+09 | 1.01E+10 | 9.60E+09 | 1.00E+10 |
| FEC [kg 1,4-DCB] | 6.40E+07 | 6.44E+07 | 6.70E+07 | 6.83E+07 | 6.50E+07 | 6.66E+07 | 6.55E+07 | 6.30E+07 | 6.88E+07 |
| MEC [kg 1,4-DCB] | 9.04E+07 | 9.15E+07 | 9.44E+07 | 9.63E+07 | 9.23E+07 | 9.48E+07 | 9.34E+07 | 9.02E+07 | 9.83E+07 |
| HCT [kg 1,4-DCB] | 3.20E+08 | 3.18E+08 | 3.35E+08 | 3.41E+08 | 3.28E+08 | 3.34E+08 | 3.27E+08 | 3.27E+08 | 3.29E+08 |
| HNCT [kg 1,4-DCB] | 3.55E+09 | 7.76E+08 | 3.14E+09 | 6.67E+09 | 1.17E+09 | 3.33E+09 | 7.86E+08 | 2.43E+09 | 3.64E+09 |
| LU [m2a crop eq] | 2.54E+08 | 2.66E+08 | 2.77E+08 | 2.88E+08 | 2.64E+08 | 2.64E+08 | 2.54E+08 | 2.52E+08 | 2.75E+08 |
| MRS [kg Cu eq] | 1.96E+07 | 2.02E+07 | 2.08E+07 | 2.09E+07 | 2.02E+07 | 2.04E+07 | 1.95E+07 | 1.96E+07 | 2.15E+07 |
| FRS [kg oil eq] | 1.64E+09 | 1.59E+09 | 1.63E+09 | 1.67E+09 | 1.63E+09 | 1.65E+09 | 1.60E+09 | 1.59E+09 | 1.68E+09 |
| WC [m3] | 1.01E+08 | 6.63E+07 | 5.54E+07 | 6.39E+07 | 6.68E+07 | 3.42E+07 | 1.10E+08 | 3.72E+07 | 4.64E+07 |

A)




B)




(continue in the next page)

C)

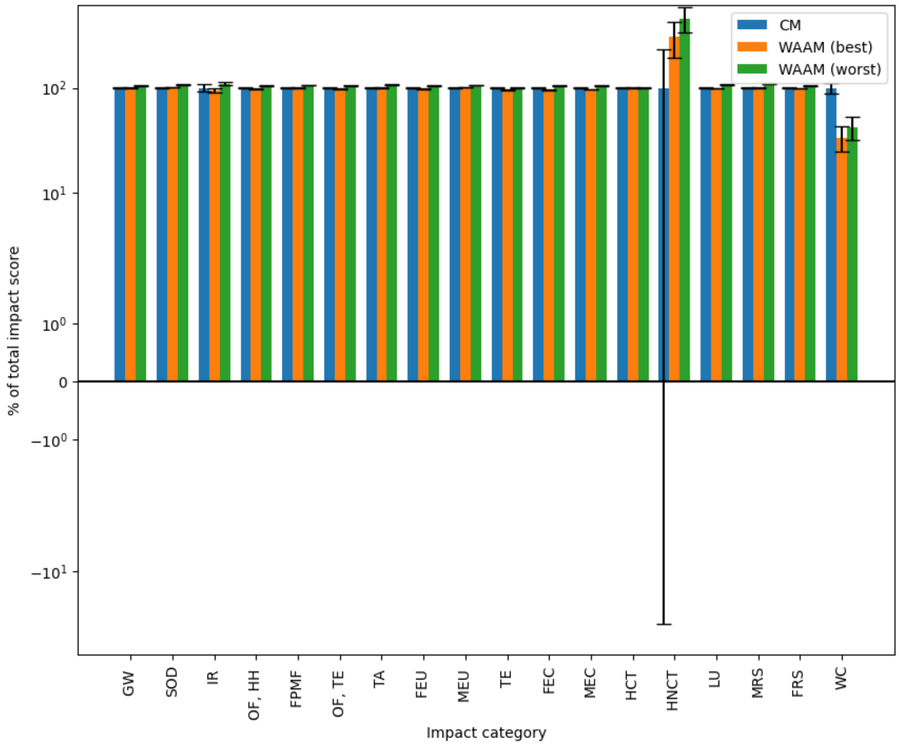



**Figure 5.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator A-1 (A) small, (B) medium, and (C) large with uncertainty calculated with Monte Carlo analysis for model parameters. For small ship propeller: conventional manufacturing (CM) is worse than WAAM (best) in 8 out of 18 impact categories, while CM is better than WAAM (worst) in 15 out of 18 impact categories. For medium ship propeller: conventional manufacturing (CM) is worse than WAAM (best) in 17 out of 18 impact categories, while CM is better than WAAM (worst) in 4 out of 18 impact categories. For large ship propeller: conventional manufacturing (CM) is worse than WAAM (best) in 11 out of 18 impact categories, while CM is better than WAAM (worst) in 16 out of 18 impact categories. The impact categories "Human non-carcinogenic toxicity" illustrates significant uncertainty.*

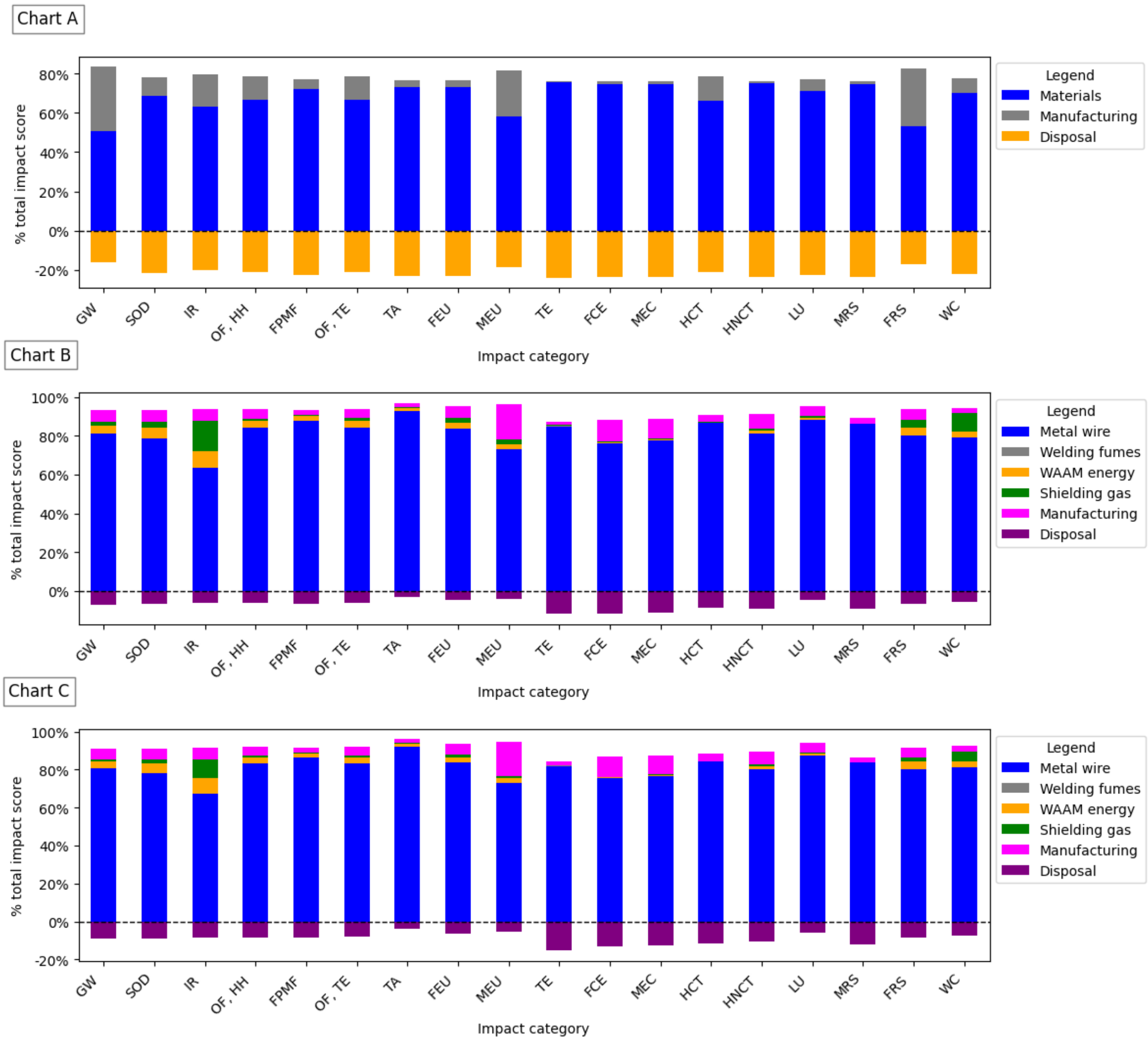



**Figure 6.** *Process contribution of MAN ship propeller (excluding the use stage as it would be the most contributing process) produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). Looking at (A) the material for the casted ship propeller is the most contributing process. For WAAM (i.e., (B) and (C)) the most contributing process are the metal wires (Inconel 625 and Steel 355). For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis. The process contribution analysis for medium and large boat propeller are not shown here as they are the same as medium and large ship propellers LCI unit processes were increased proportionally (if Monte Carlo analysis is not used).*

### 3.1.2 Life Cycle Costing (LCC)

**Table 4.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator A-1.*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per propeller (€) | Cost bronze casted blade, hub and hub cylinder block (€) | |
| | Milling - total (€) | Milling - Manual labor (€/h) |
| | | Milling (h) |
| **Operational (use of ship propeller)** | | |
| Fuel consumption cost (€/yr) | Fuel cost (€/t) | |
| | Fuel consumption (t/yr) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per propeller (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **Operational (use of ship propeller)** | | |
| Fuel consumption cost (€/yr) | Fuel cost (€/t) | |
| | Fuel consumption (t/yr) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

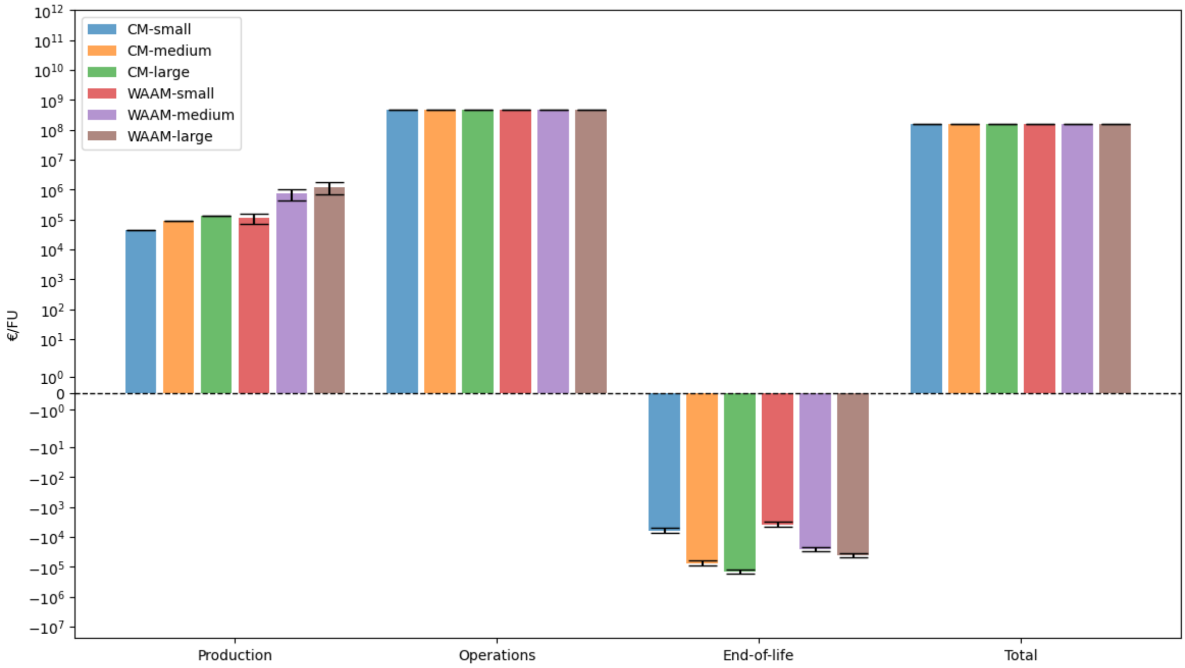



**Figure 7.** *Illustration of financial life cycle cost of demonstrator A-1.*

**Table 5.** *Comparison of costs between casted and WAAM propeller demonstrator A-1.*

| | Casted small propeller | WAAM small propeller | Casted medium propeller | WAAM medium propeller | Casted large propeller | WAAM large propeller |
|---|---|---|---|---|---|---|
| Production Costs (€\FU) | 4.51E+04 | 1.53E+05 to 7.15E+04 | 9.06E+04 | 4.34E+05 to 1.06E+06 | 1.36E+05 | 7.01E+05 to 1.78E+06 |
| Operational costs (€\FU) | 4.800E+08 | 4.795E+08 to 4.800E+08 | 4.800E+08 | 4.795E+08 to 4.800E+08 | 4.800E+08 | 4.795E+08 to 4.800E+08 |
| Revenue-recyclables (€\FU) | 5.09E+03 to 7.12E+03 | 3.02E+03 to 4.46E+03 | 6.28E+04 to 8.80E+04 | 2.14E+04 to 3.10E+04 | 1.24E+05 to 1.74E+05 | 3.45E+04 to 4.95E+04 |

## 3.2. Demonstrator A-2b

This demonstrator is a holding ring used in EDF hydraulic power plant. The final part weigh around 300 kg and the maximum outer diameter is 1220mm, the inner diameter is 850mm and the height is 170mm. When multi-material Wire Arc Additive Manufacturing (WAAM) is employed, the part performance should be better due to improved corrosion and wear resistance. Particularly, it is expected that the areas exposed to water will be less sensitive to abrasion and corrosion as, compared with the current practice, the use of a martensitic alloy in areas in contact with water would provide a better corrosion resistance. Scratches on CuAl part will be the same as for CM.
Lead time is estimated to be potentially reduced from 36 to 12 weeks with WAAM.

### 3.2.1 Life Cycle Assessment (LCA)

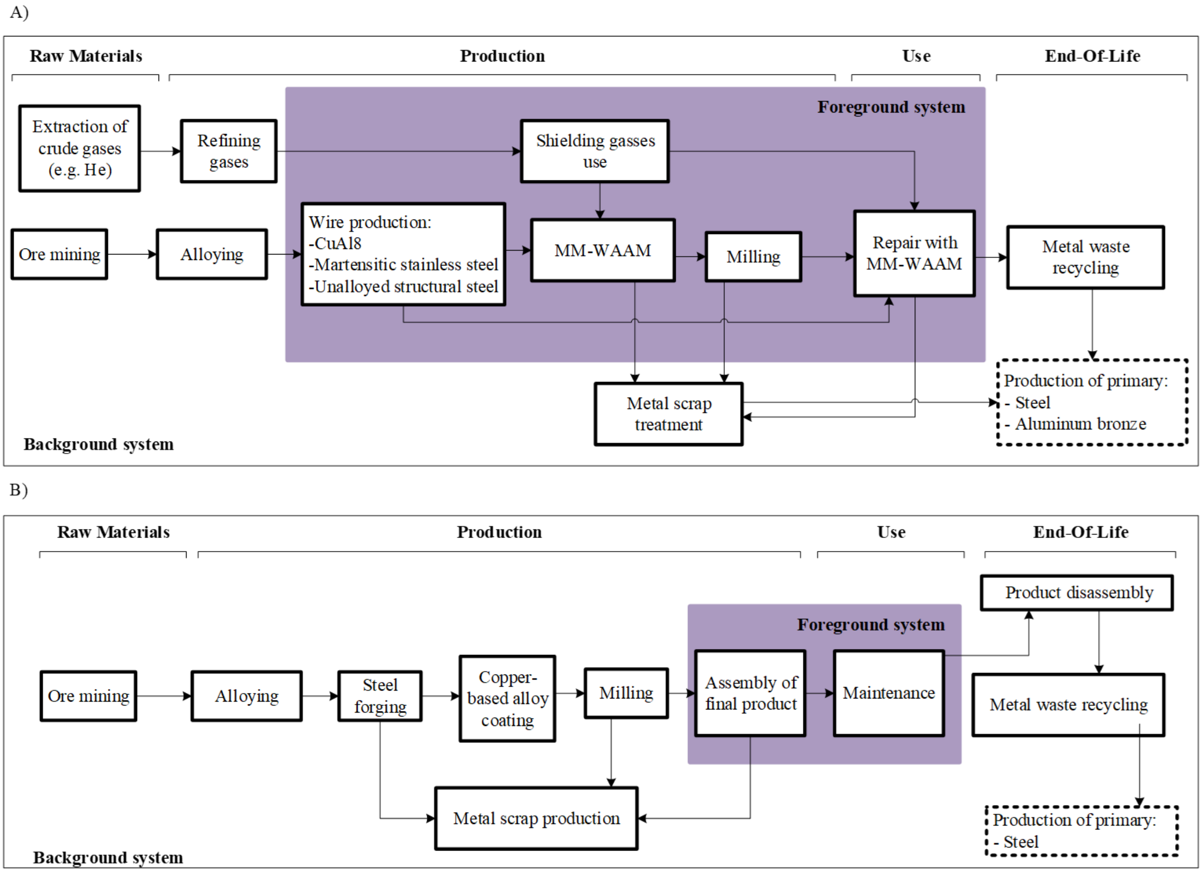



**Figure 8.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured EDF holding ring. Note: MM-WAAM = multi-material wire arc additive manufacturing.*

**Table 6.** *Summary of scenario sensitivity analysis of EDF holding ring. Note that data and assumptions are based on the last meeting with the project partners on 21 - 11 - 2023.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized production concept (80 kg of AM410, 300 kg of AM460, 7 kg of AM CUAl8)<br>• Optimized shielding gas flow (15 L/min) | • R&D production concept (180 kg of AM410, 320 kg of AM460, 7 kg of AM CUAl8)<br>• Current shielding gas flow (20 L/min) |
| Use stage | | • Addition of 10 kg of material for half repairs in comparison to current practice during part lifetime; | • Addition of 10 kg of material for the same repairs as for the current practice during part lifetime; |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 7.** *Characterized results A-2b ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 6.72E+03 | 3.50E+03 | 5.43E+03 |
| SOD [kg CFC11 eq] | 1.44E-03 | 1.34E-03 | 1.99E-03 |
| IR [kBq Co-60 eq] | 2.48E+02 | 8.16E+02 | 1.07E+03 |
| OF, HH [kg NOx eq] | 1.44E+01 | 8.82E+00 | 1.33E+01 |
| FPMF [kg PM2.5 eq] | 1.15E+01 | 7.27E+00 | 1.14E+01 |
| OF, TE [kg NOx eq] | 1.54E+01 | 9.25E+00 | 1.40E+01 |
| TA [kg SO2 eq] | 1.64E+01 | 1.51E+01 | 2.17E+01 |
| FEU [kg P eq] | 2.98E+00 | 2.94E+00 | 4.12E+00 |
| MEU [kg N eq] | 4.75E-01 | 2.41E-01 | 4.07E-01 |
| TE [kg 1,4-DCB] | 5.89E+04 | 5.43E+04 | 8.33E+04 |
| FEC [kg 1,4-DCB] | 3.97E+02 | 6.55E+02 | 9.71E+02 |
| MEC [kg 1,4-DCB] | 5.70E+02 | 8.62E+02 | 1.28E+03 |
| HCT [kg 1,4-DCB] | 2.91E+03 | 1.26E+03 | 2.63E+03 |
| HNCT [kg 1,4-DCB] | 6.18E+03 | 1.52E+04 | 1.47E+04 |
| LU [m2a crop eq] | 1.50E+02 | 3.39E+02 | 5.73E+02 |
| MRS [kg Cu eq] | 1.64E+02 | 1.14E+02 | 1.94E+02 |
| FRS [kg oil eq] | 1.47E+03 | 9.51E+02 | 1.47E+03 |
| WC [m3] | 9.97E+01 | 3.84E+02 | 1.29E+03 |

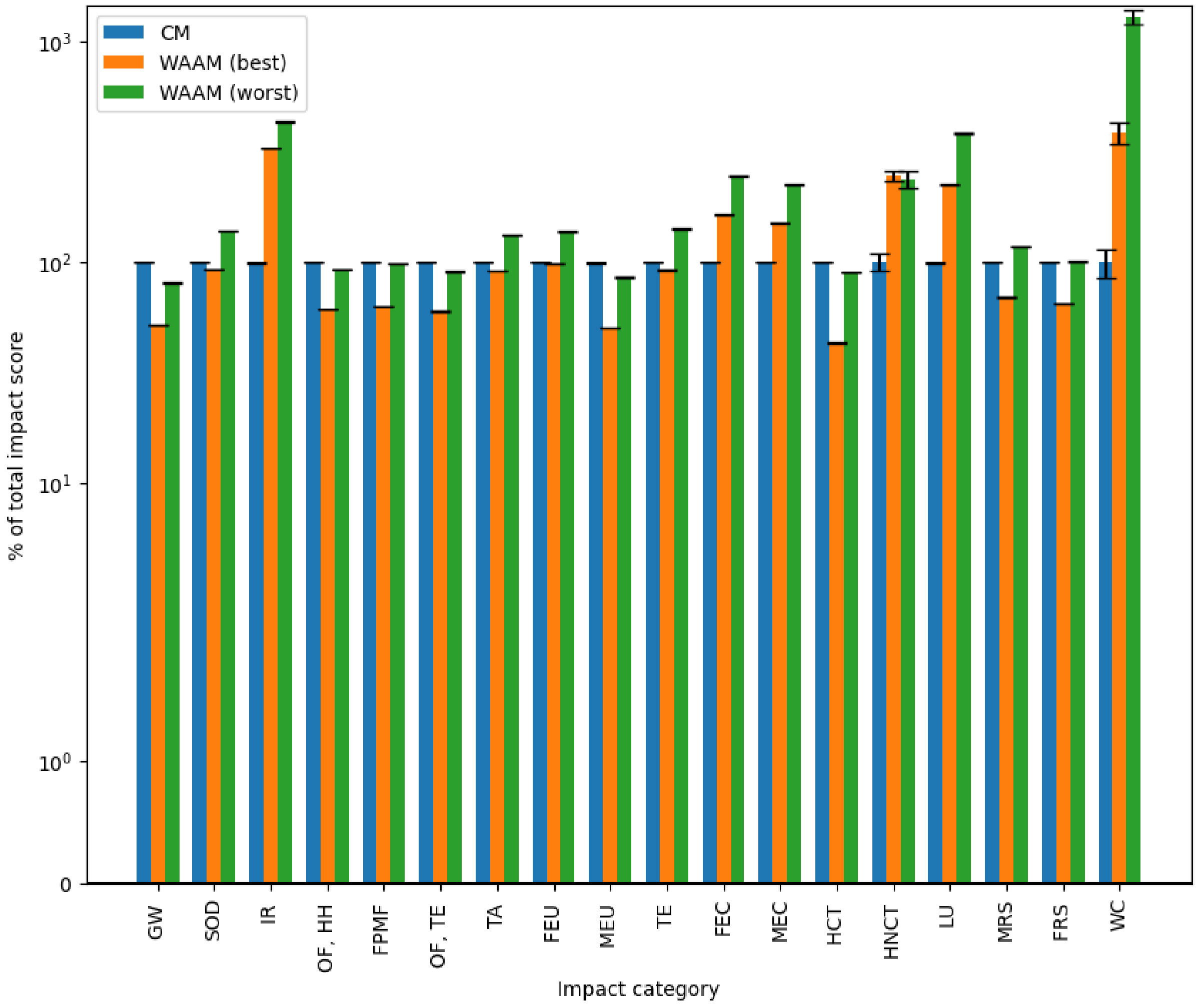



**Figure 9.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator A-2b with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) in 12 out of 18 impact categories, while CM is better than WAAM (worst) in 12 out of 18 impact categories. Y-axis is in logscale.*

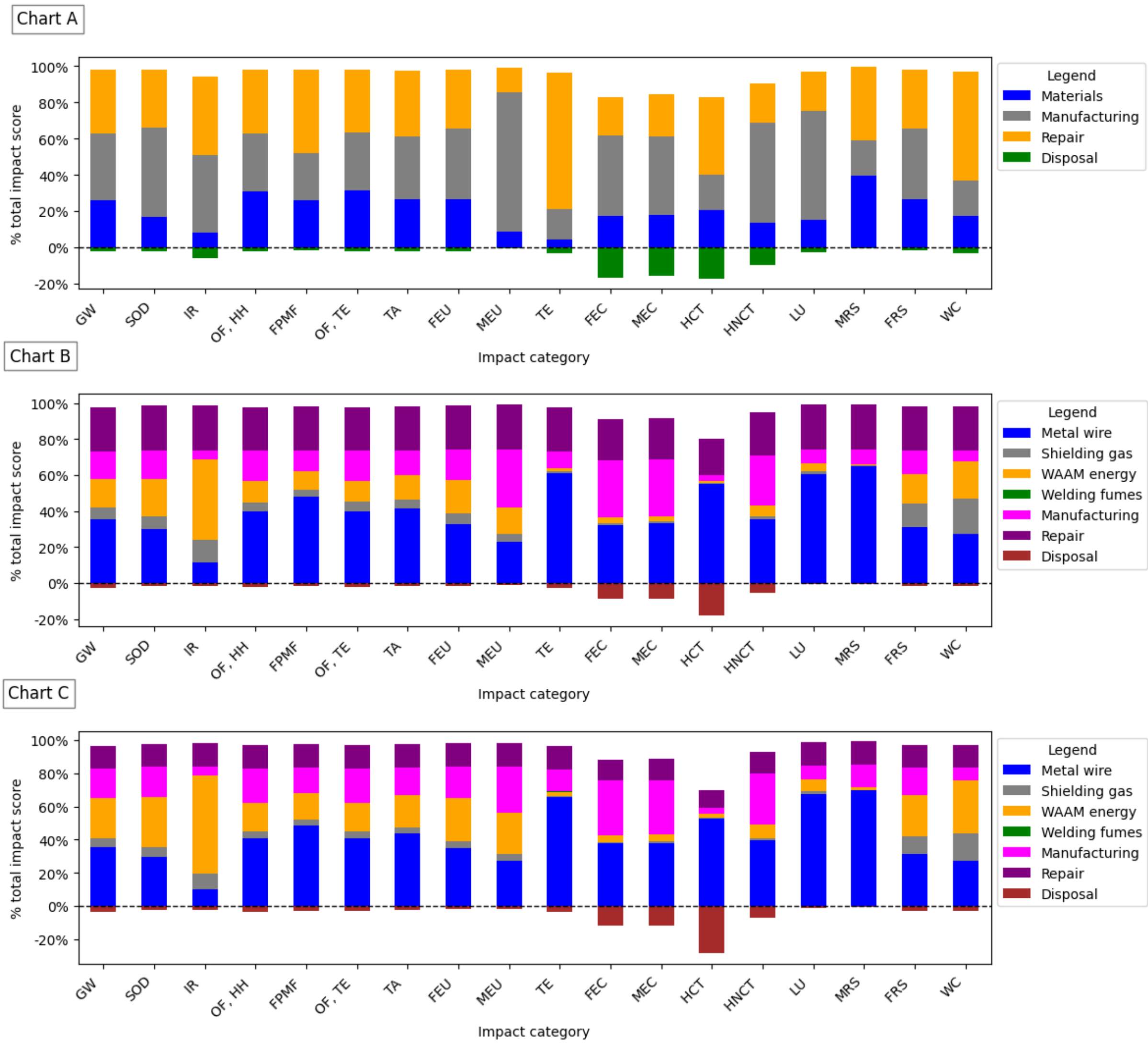



**Figure 10.** *process contribution of EDF holding ring produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the steel forging process is the most contributing process except for Terrestrial ecotoxicity for which the repair is the most relevant process. For WAAM (i.e., (B) and (C)) the most contributing process is the metal wire production, except for Ionizing radiation that is dominated by "WAAM energy". As major difference between WAAM worst and best we can notice the different contribution to the overall impact from "Repair" which is more relevant for WAAM worst. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.2.2 Life Cycle Costing (LCC)

**Table 8.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator A-2b.*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per holding ring (€) | Cost steel block (€) | |
| | Mould for casting (€) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per holding ring (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | Time for deposition (h) | |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

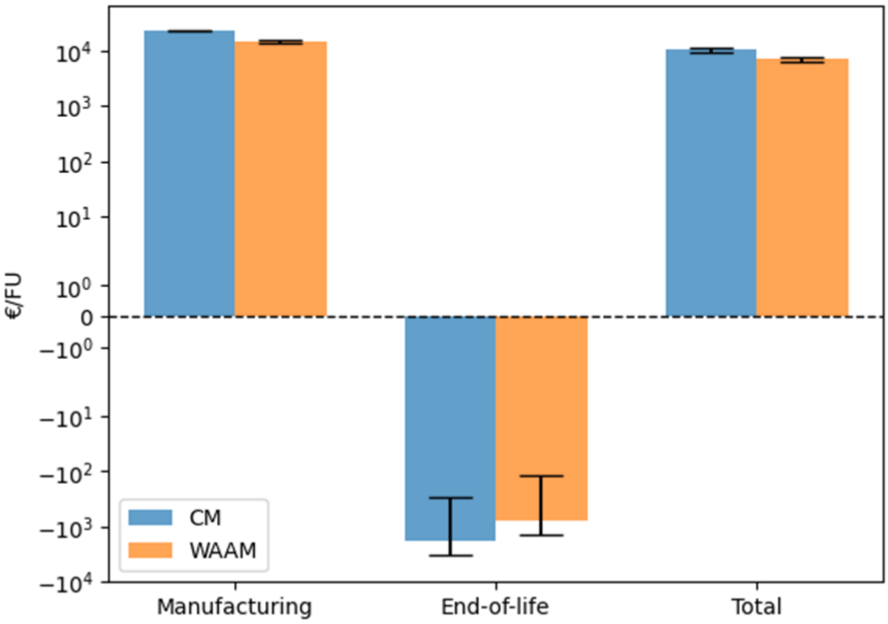



**Figure 11.** *illustration of financial life cycle cost of EDF holding ring. Note: FU = functional unit.*

**Table 9.** *Comparison between conventional and WAAM production demonstrator A-2b.*

| | Production costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|
| **Conventional holding ring** | 2.26E+04 | 3.01E+02 to 3.39E+03 |
| **WAAM holding ring** | 1.55E+04 to 1.43E+04 | 1.20E+02 to 1.44E+03 |

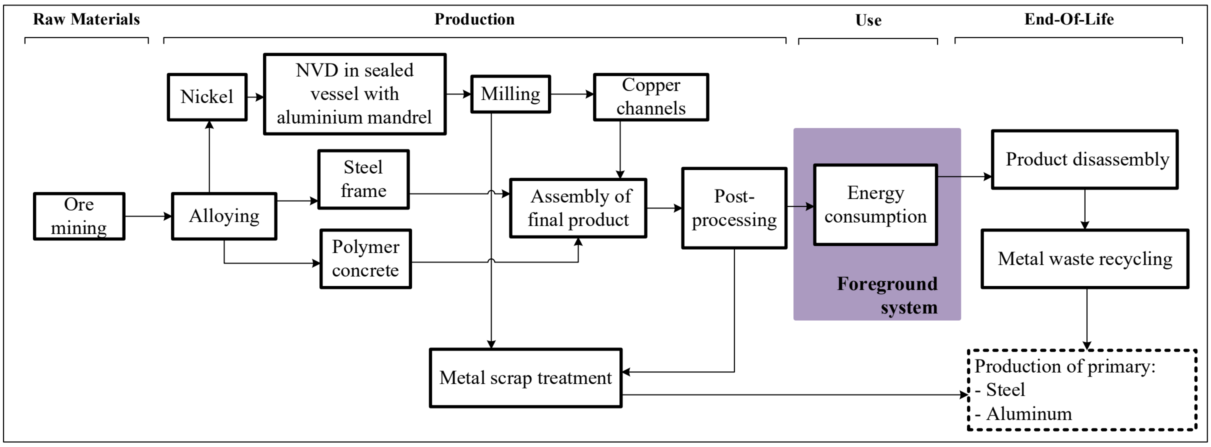
## 3.3. Demonstrator B-1

This demonstrator is a bathtub mould for production of quartz-filled resin (methyl methacrylate) bathtubs by Villeroy & Boch. It is constituted of a showface and a backface. In this analysis only the showface is considered for comparative purposes as the current suppliers are far away (i.e., Canada) and Nickel Vapor Deposition (NVD) process with a one-use aluminum mandrel is used, which is not optimally from resource-efficient point of view. In alternative, Wire Arc Additive Manufacturing (WAAM) is used for its production using structural steel grade (S355) and martensitic stainless steel

(S410). With those, it was possible to reach the same mirror-like surface and without the surface waviness seen with Ni-based alloys. In this case, during the demonstrator testing they noticed that the heat transfer through the cooling channels is faster in case the mould is fabricated with WAAM, and this can lead to approximately 10% energy savings during the use of it to produce bathtubs.
Additionally, the lead time can be reduced from 16-20 weeks to 5 weeks. As conventionally produced showface mould is manufactured in Canada, while WAAM is fabricated in Netherlands and Germany.

### 3.3.1 Life Cycle Assessment (LCA)

A)




B)

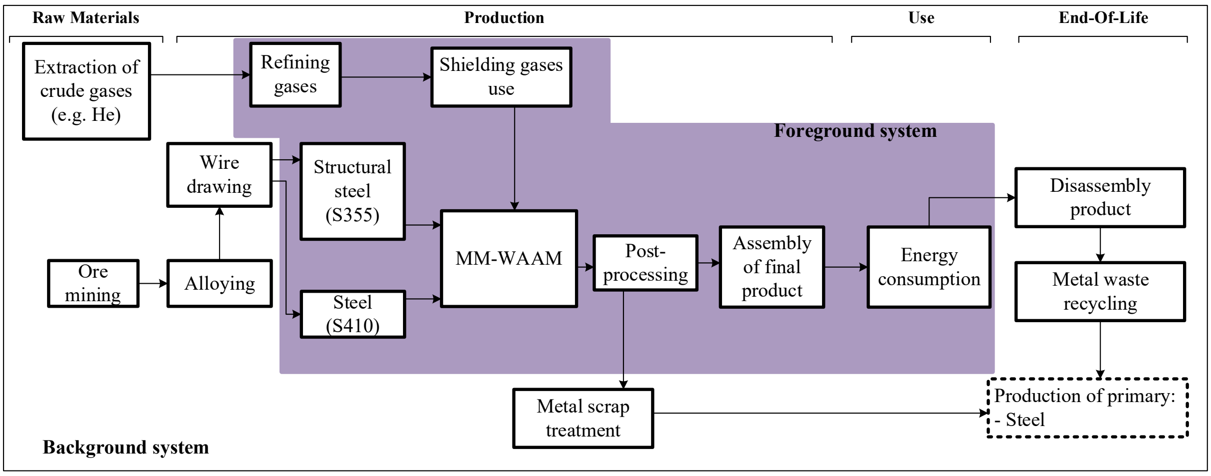



**Figure 12.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured Villeroy&Boch bathtub showface mould. Note: MM-WAAM = multi-material wire arc additive manufacturing, NVD = Nickel Vapor Deposition (NVD) process.*

**Table 10.** *Summary of scenario sensitivity analysis of Villeroy&Boch bathtub showface mould. Note that data and assumptions are based on the last meeting with the project partners on 28 - 06 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized shielding gas flow (15 L/min) | • Current shielding gas flow (20 L/min) |
| Use stage | | • Addition of 100 g for 10 repairs during mould lifespan;<br>• 10% energy savings during mould use. | • Addition of 200 g for 10 repairs during mould lifespan (same as the current practice);<br>• No energy savings during use of mould |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 11.** *Characterized results B-1 ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 7.41E+06 | 6.98E+04 | 7.74E+04 |
| SOD [kg CFC11 eq] | 3.39E+00 | 3.19E-02 | 3.53E-02 |
| IR [kBq Co-60 eq] | 4.21E+06 | 4.01E+04 | 4.42E+04 |
| OF, HH [kg NOx eq] | 1.33E+04 | 1.25E+02 | 1.40E+02 |
| FPMF [kg PM2.5 eq] | 1.02E+04 | 9.05E+01 | 1.03E+02 |
| OF, TE [kg NOx eq] | 1.39E+04 | 1.30E+02 | 1.45E+02 |
| TA [kg SO2 eq] | 2.49E+04 | 2.35E+02 | 2.62E+02 |
| FEU [kg P eq] | 6.46E+03 | 6.31E+01 | 6.95E+01 |
| MEU [kg N eq] | 5.11E+02 | 4.89E+00 | 5.37E+00 |
| TE [kg 1,4-DCB] | 1.11E+07 | 6.69E+04 | 9.74E+04 |
| FEC [kg 1,4-DCB] | 2.99E+05 | 3.58E+03 | 3.95E+03 |
| MEC [kg 1,4-DCB] | 3.95E+05 | 4.69E+03 | 5.20E+03 |
| HCT [kg 1,4-DCB] | 4.81E+05 | 4.12E+03 | 5.66E+03 |
| HNCT [kg 1,4-DCB] | 9.10E+06 | 8.96E+04 | 9.87E+04 |
| LU [m2a crop eq] | 2.18E+05 | 2.32E+03 | 2.57E+03 |
| MRS [kg Cu eq] | 1.50E+04 | 7.44E+01 | 1.41E+02 |
| FRS [kg oil eq] | 2.01E+06 | 1.90E+04 | 2.11E+04 |
| WC [m3] | 1.37E+05 | 1.32E+03 | 1.49E+03 |

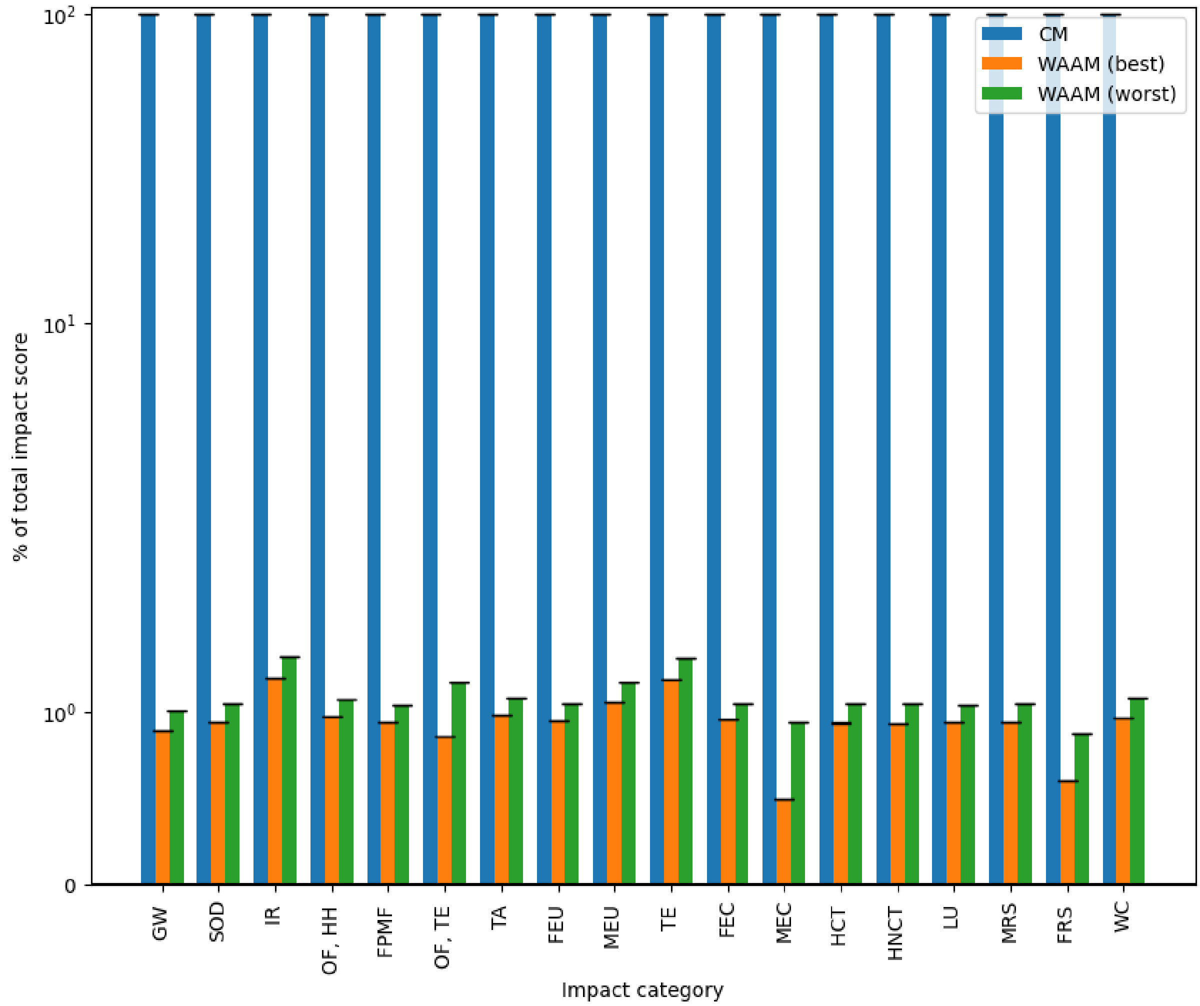



**Figure 13.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-1 with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than both WAAM (best) and WAAM (worst) in all 18 impact categories. Y-axis is in logscale.*

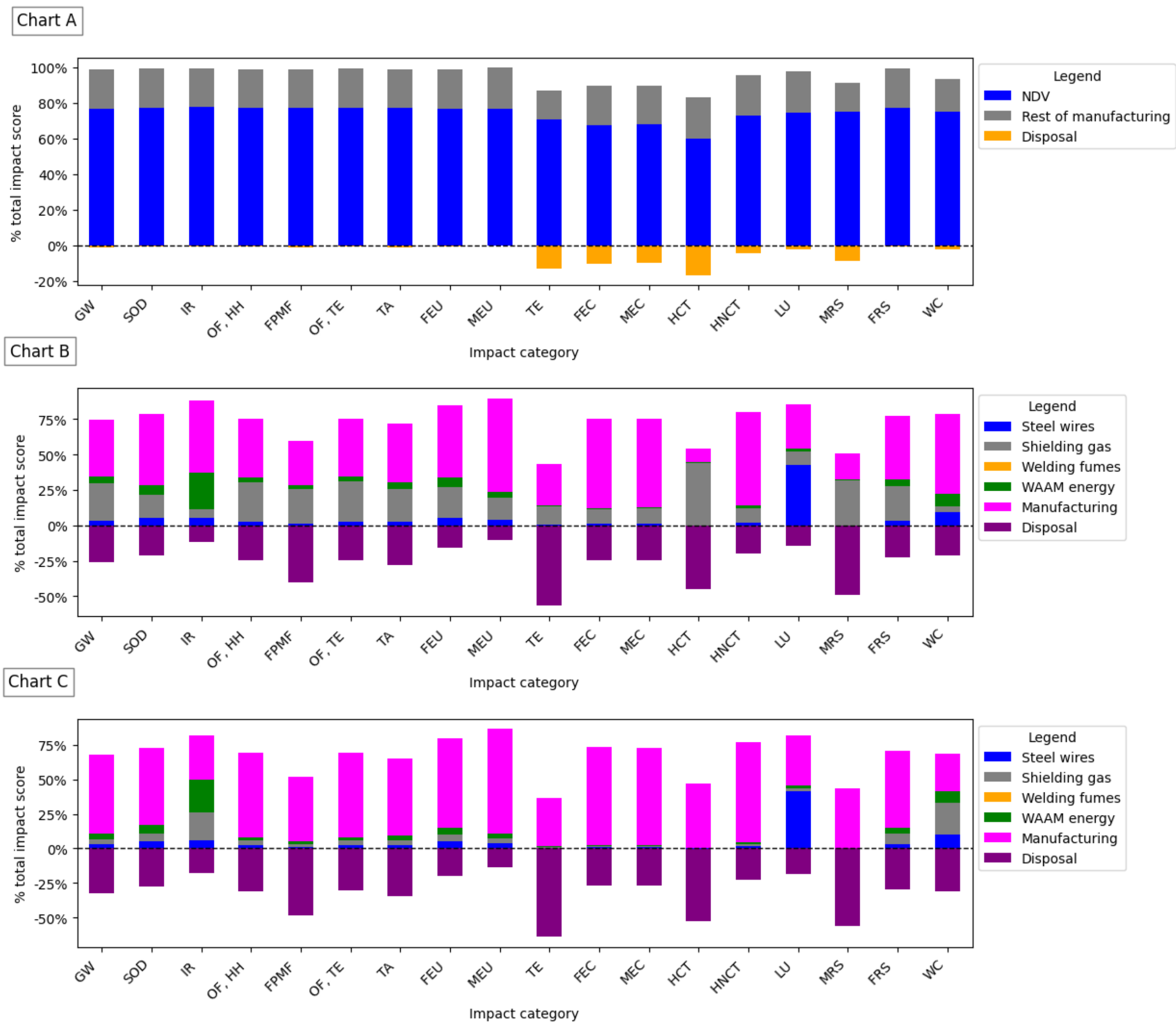



**Figure 14.** *Process contribution of Villeroy&Boch bathtub showface mould (excluding the use stage as it would be the most contributing process) produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the NDV process is the most contributing process. For WAAM (i.e., (B) and (C)) the most contributing process is the manufacturing process, except for Land use that is dominated by steel wires production. The main difference for WAAM worst and best is relative to contribution of the shielding gasses which is more relevant for worst scenario, particularly in the impact categories Human cancerogenic toxicity and Mineral resource scarcity. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.3.2 Life Cycle Costing (LCC)

**Table 12.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-1.*

| CM | | |
|---|---|---|
| COSTS | | |
| Manufacturing | | |
| Total cost per mould (€) | Cost casted showface and backface mould (€) | |
| | Machining - total (€) | Machining - Manual labour (€/h) |
| | | Machining (h) |
| REVENUE-RECYCLABLES | | |
| Recycling - Scrapping value (€/product) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

| WAAM | | |
|---|---|---|
| COSTS | | |
| Manufacturing | | |
| Total cost per bathtub mould (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| REVENUE-RECYCLABLES | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

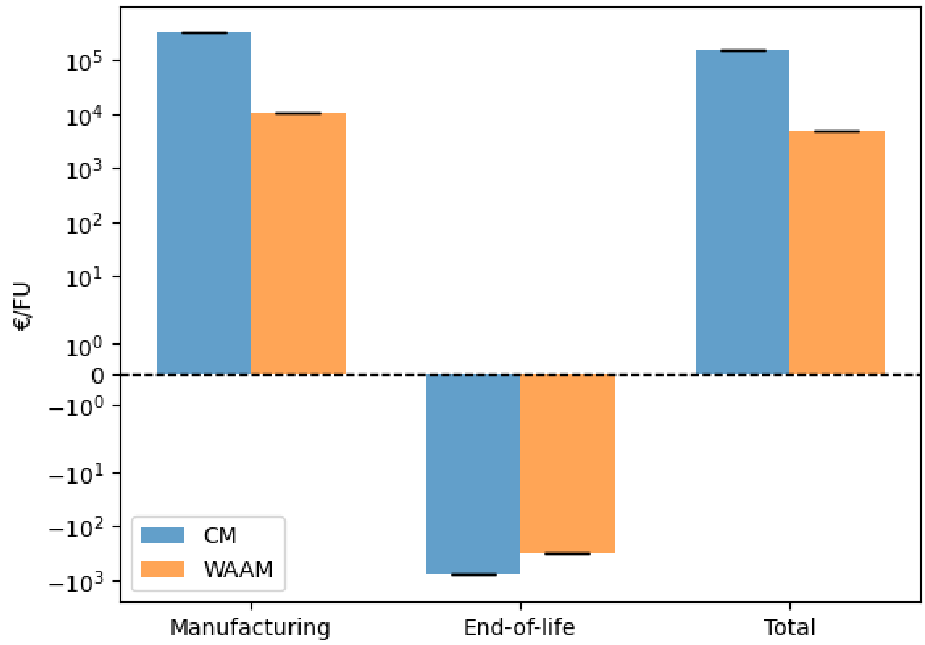



**Figure 15.** *Illustration of financial life cycle cost of Villeroy&Boch bathtub showface mould.*

**Table 13.** *Comparison between conventional and WAAM production demonstrator B-1.*

| | Lifecycle costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|
| **Conventional bathtub mould** | 3.15E+05 | 7.96E+02 |
| **WAAM bathtub mould** | 1.04E+04 | 3.12E+02 |

## 3.4. Demonstrator B-2

This demonstrator is a mandrel tool for production of composite aerospace parts by GKN. Wire Arc Additive Manufacturing (WAAM) is tested for its production and a topology optimized inspired design is achieved for the mandrel tool. The maintenance and use of the mandrel tool is the same for conventional and WAAM alternatives. Due to system equivalency in LCA, this the use life cycle stage can be disregarded.

Lead time is estimated to be potentially reduced of 92% with WAAM.

### 3.4.1 Life Cycle Assessment (LCA)

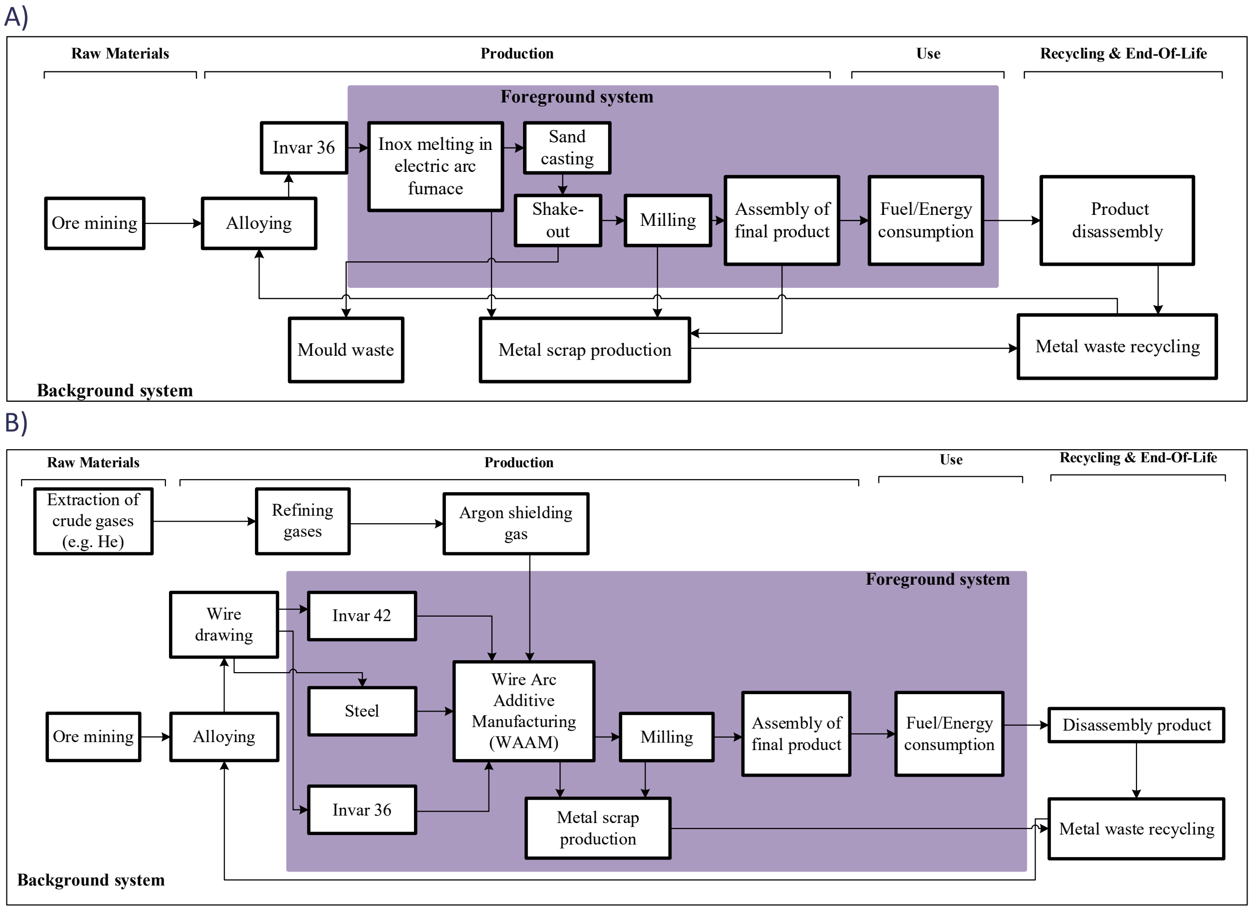



**Figure 16.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured GKN mandrel tool. Note: MM-WAAM = multi-material wire arc additive manufacturing.*

**Table 14.** *Summary of scenario sensitivity analysis of GKN mandrel tool. Note that data and assumptions are based on the last meeting with the project partners on 28 - 06 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized production concept with use of both FeNi36 and FeNi55 and reduced amount of added material with WAAM (200 kg)<br>• Optimized shielding gas flow (15 L/min) | • R&D production concept (only FeNi36 and is 261 kg)<br>• Current shielding gas flow (20 L/min) |
| Use stage | | • Equivalent to current practice | • Equivalent to current practice |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 15.** *Characterized results B-2 ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 4.73E+03 | 1.07E+03 | 1.99E+03 |
| SOD [kg CFC11 eq] | 1.98E-03 | 6.50E-04 | 1.19E-03 |
| IR [kBq Co-60 eq] | 3.73E+02 | 1.82E+02 | 3.15E+02 |
| OF, HH [kg NOx eq] | 1.27E+01 | 3.57E+00 | 6.75E+00 |

| | | | |
|---|---|---|---|
| FPMF [kg PM2.5 eq] | 2.75E+01 | 1.46E+01 | 2.87E+01 |
| OF, TE [kg NOx eq] | 1.31E+01 | 3.72E+00 | 7.01E+00 |
| TA [kg SO2 eq] | 7.92E+01 | 4.59E+01 | 9.01E+01 |
| FEU [kg P eq] | 3.16E+00 | 9.13E-01 | 1.68E+00 |
| MEU [kg N eq] | 6.20E-01 | 7.96E-02 | 1.63E-01 |
| TE [kg 1,4-DCB] | 1.48E+05 | 8.83E+04 | 1.74E+05 |
| FEC [kg 1,4-DCB] | 7.61E+02 | 3.16E+02 | 6.24E+02 |
| MEC [kg 1,4-DCB] | 1.04E+03 | 4.37E+02 | 8.63E+02 |
| HCT [kg 1,4-DCB] | 9.98E+02 | 6.36E+02 | 1.16E+03 |
| HNCT [kg 1,4-DCB] | 1.43E+04 | 5.94E+03 | 1.13E+04 |
| LU [m2a crop eq] | 1.17E+03 | 1.65E+02 | 2.38E+02 |
| MRS [kg Cu eq] | 2.57E+02 | 1.54E+02 | 3.09E+02 |
| FRS [kg oil eq] | 1.11E+03 | 3.04E+02 | 5.47E+02 |
| WC [m3] | 6.84E+01 | 7.82E+01 | 1.10E+02 |

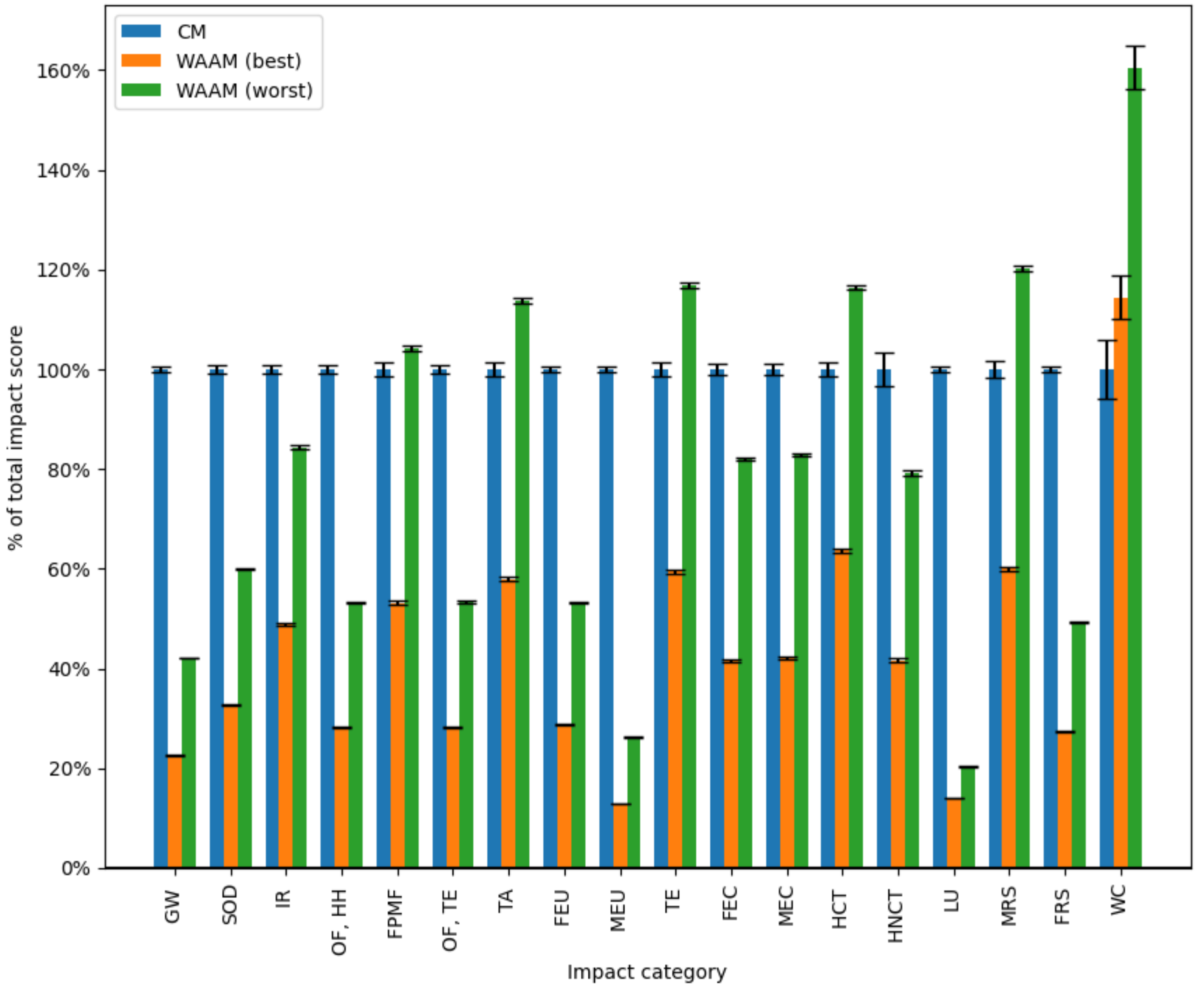



**Figure 17.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-2 with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) in 17 out of 18 impact categories, while CM is better than WAAM (worst) in 6 out of 18 impact categories.*

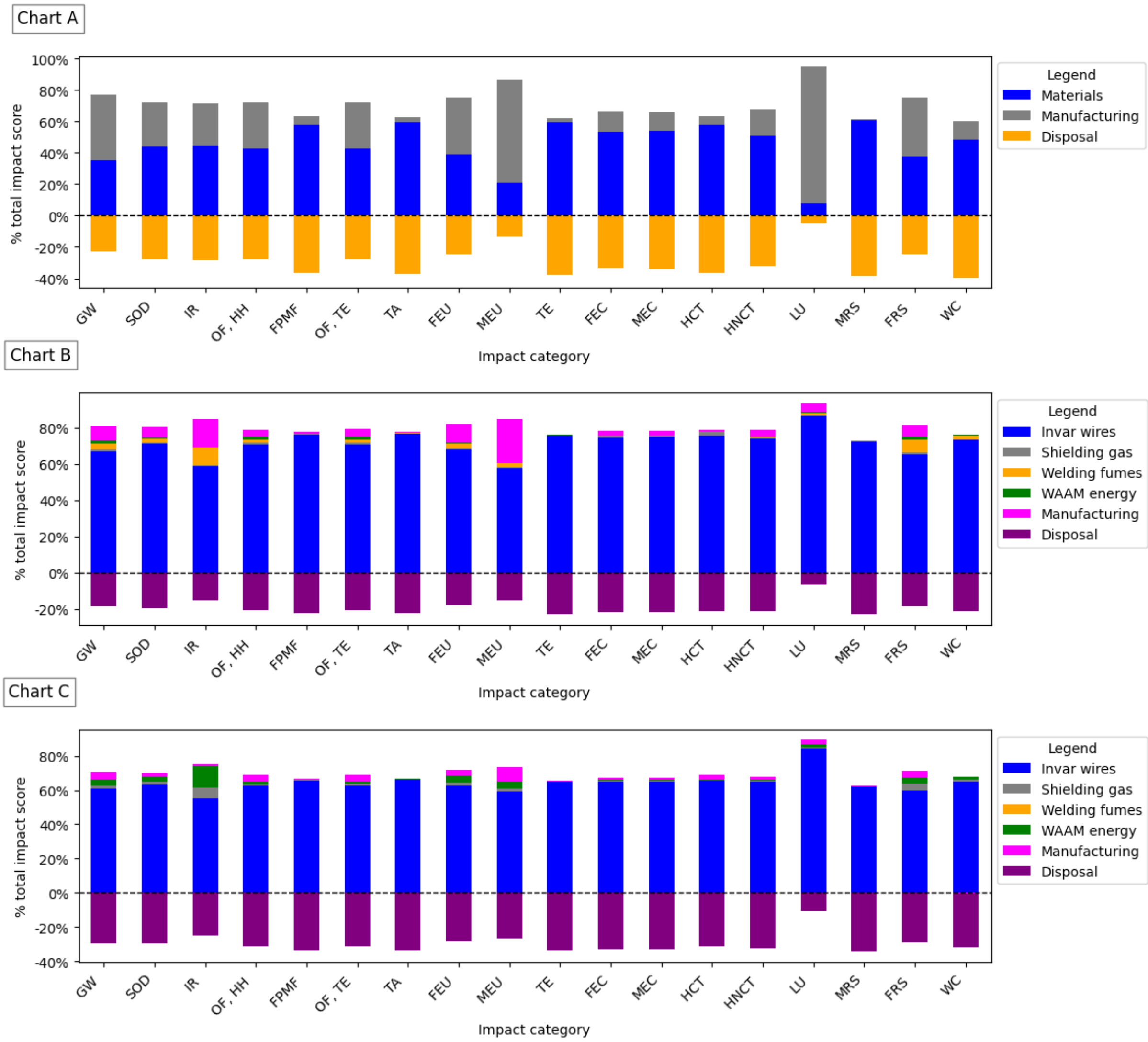



**Figure 18.** *Process contribution of GKN mandrel tool produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the materials life cycle stage is the most contributing process except for Marine Eutrophication and Land use for which the manufacturing (including casting, milling and transportation) is the most relevant life cycle stage. For WAAM (i.e., (B) and (C)) the most contributing process is the metal wire production. The main different between WAAM worst and best is the fact that in Ionizing radiation and Mineral resource scarcity welding fumes and WAAM energy are the most contributing processes, respectively. Additionally, in WAAM (worst) the manufacturing stage contributes generally more than in WAAM (best). For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.4.2 Life Cycle Costing (LCC)

**Table 16.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-2.*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per tool (€) | | Cost casted mandrel tool (€) |
| | Machining - total (€) | Machining - Manual labour (€/h) |
| | | Machining (h) |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | | Recycling disposed product (kg/product) |
| | | Sold scrap from product machining (€/kg) |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per mandrel tool (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

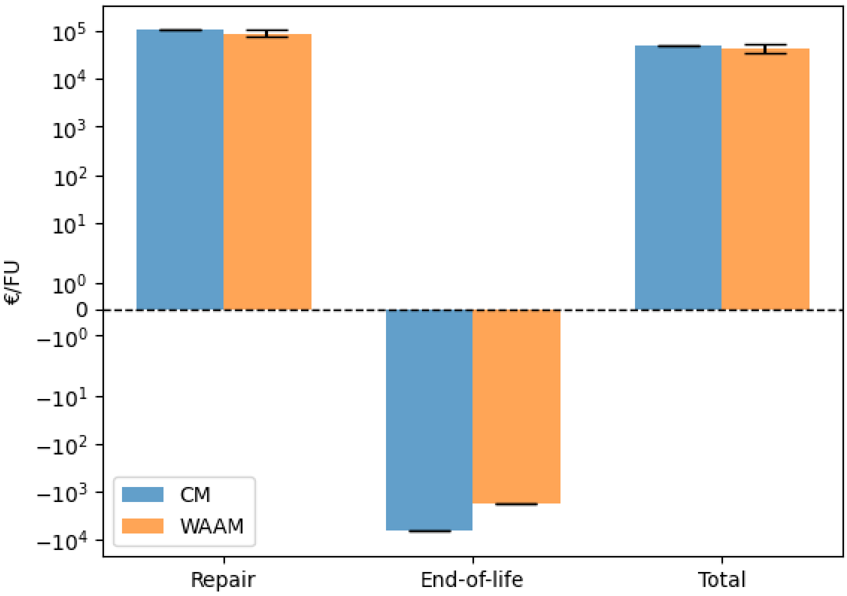



**Figure 19.** *Illustration of financial life cycle cost of GKN mandrel tool. Note: FU = functional unit.*

**Table 17.** *Comparison between conventional and WAAM production demonstrator B-2.*

| | Production costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|
| **Conventional mandrel tool** | 1.06E+05 | 6.77E+03 |
| **WAAM mandrel tool** | 7.62E+04 to 1.06E+05 | 1.80E+03 |

## 3.5. Demonstrator B-3b

This demonstrator is an injection mould for plastic optical fiber closure used by Shapers. The mould is composed of a fixed and a mobile half. A hybrid manufacturing approach combining Wire Arc Additive Manufacturing (WAAM) with iron casting is used its fixed and moving halves production. With WAAM 25% energy savings thanks to rheological analysis based on design cooling channels (lower distance between plastic part and cooling channel) and 20% prolonged lifetime.
The lead time is estimated to be reduced of 31% in comparison to the current practice.

### 3.5.1 Life Cycle Assessment (LCA)

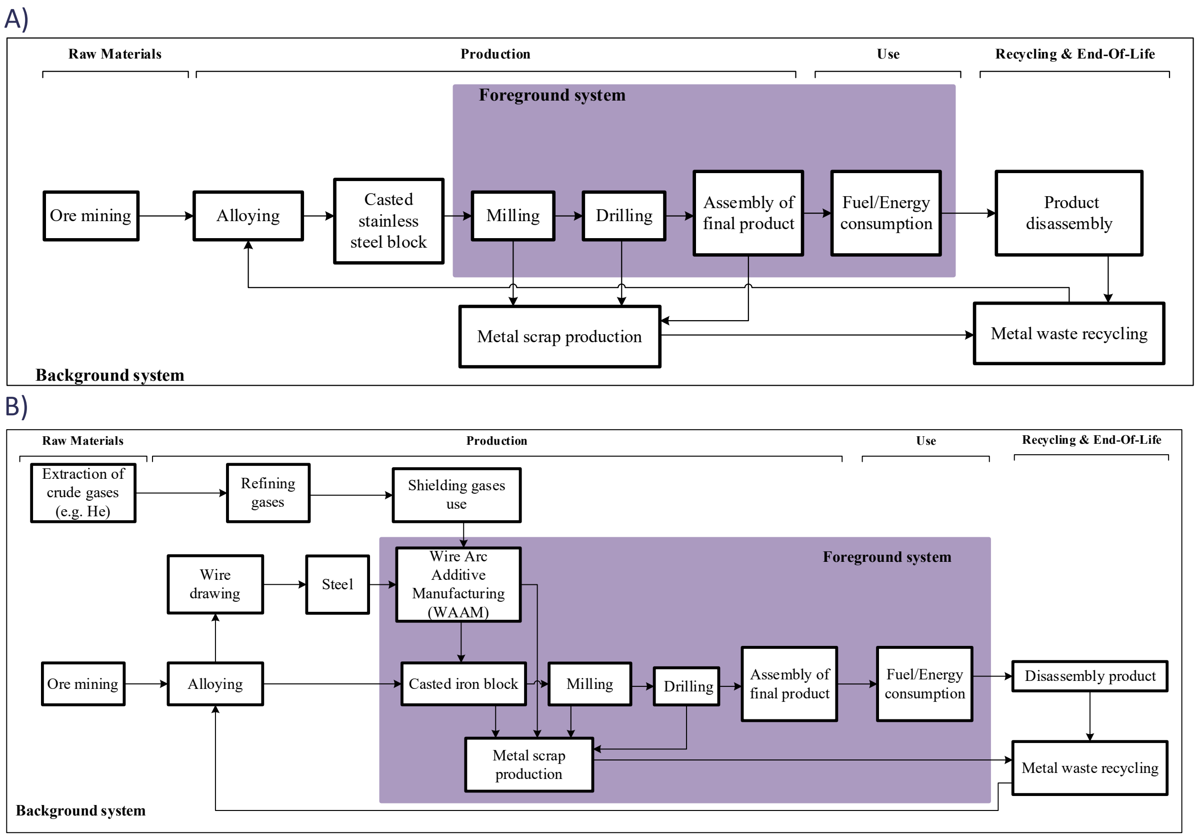



**Figure 20.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured system boundaries of Shapers injection mould.*

**Table 18.** *Summary of scenario sensitivity analysis of Shapers injection mould. Note that data and assumptions are based on the last meeting with the project partners on 12 - 12 - 2023.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized shielding gas flow (15 L/min) | • Current shielding gas flow (20 L/min) |
| Use stage | | • 25% energy savings during injection mould use thanks to design for cooling channels (lower distance between plastic part and cooling channel)<br>• 20% prolonged lifetime (20.4 years).<br>• Repair of the injection mould with WAAM every two years | • No energy savings during injection mould use<br>• Same lifetime as conventionally manufactured injection mould (17 years).<br>• Repair of the injection mould with WAAM every year as for conventionally manufactured injection mould |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 19.** *Characterized results B-3b ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 4.58E+05 | 2.79E+05 | 2.85E+05 |
| SOD [kg CFC11 eq] | 2.36E-01 | 1.55E-01 | 1.62E-01 |
| IR [kBq Co-60 eq] | 5.35E+05 | 4.13E+05 | 3.94E+05 |
| OF, HH [kg NOx eq] | 1.13E+03 | 7.71E+02 | 7.86E+02 |
| FPMF [kg PM2.5 eq] | 7.39E+02 | 3.81E+02 | 3.86E+02 |
| OF, TE [kg NOx eq] | 1.26E+03 | 8.89E+02 | 9.05E+02 |
| TA [kg SO2 eq] | 1.46E+03 | 9.74E+02 | 1.00E+03 |
| FEU [kg P eq] | 1.42E+02 | 7.75E+01 | 8.08E+01 |
| MEU [kg N eq] | 4.56E+01 | 2.93E+01 | 2.98E+01 |
| TE [kg 1,4-DCB] | 2.52E+06 | 1.37E+06 | 1.40E+06 |
| FEC [kg 1,4-DCB] | 2.49E+04 | 1.62E+04 | 1.68E+04 |
| MEC [kg 1,4-DCB] | 3.30E+04 | 2.12E+04 | 2.20E+04 |
| HCT [kg 1,4-DCB] | 7.54E+04 | 2.51E+04 | 2.82E+04 |
| HNCT [kg 1,4-DCB] | 6.64E+05 | 3.97E+05 | 2.56E+05 |
| LU [m2a crop eq] | 4.89E+04 | 4.78E+04 | 4.68E+04 |
| MRS [kg Cu eq] | 9.65E+03 | 4.24E+03 | 4.33E+03 |
| FRS [kg oil eq] | 1.91E+05 | 1.47E+05 | 1.48E+05 |
| WC [m3] | 1.62E+05 | 3.02E+05 | 1.98E+05 |

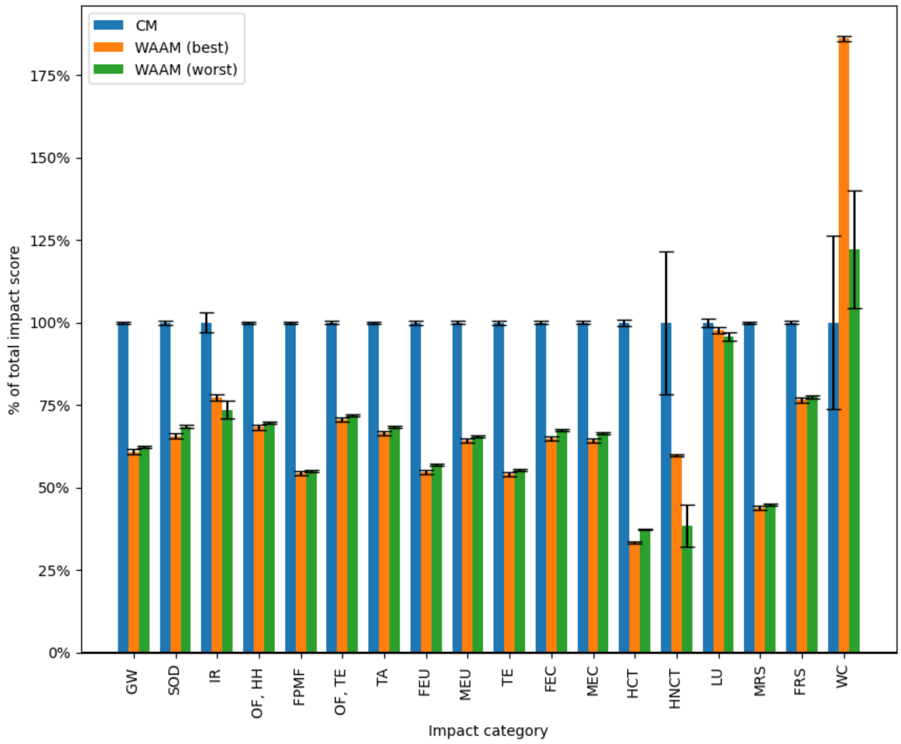



**Figure 21.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-3b with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) and (worst) in 17 out of 18 impact categories, and CM is better than WAAM (worst) in 1 out of 18 impact categories.*

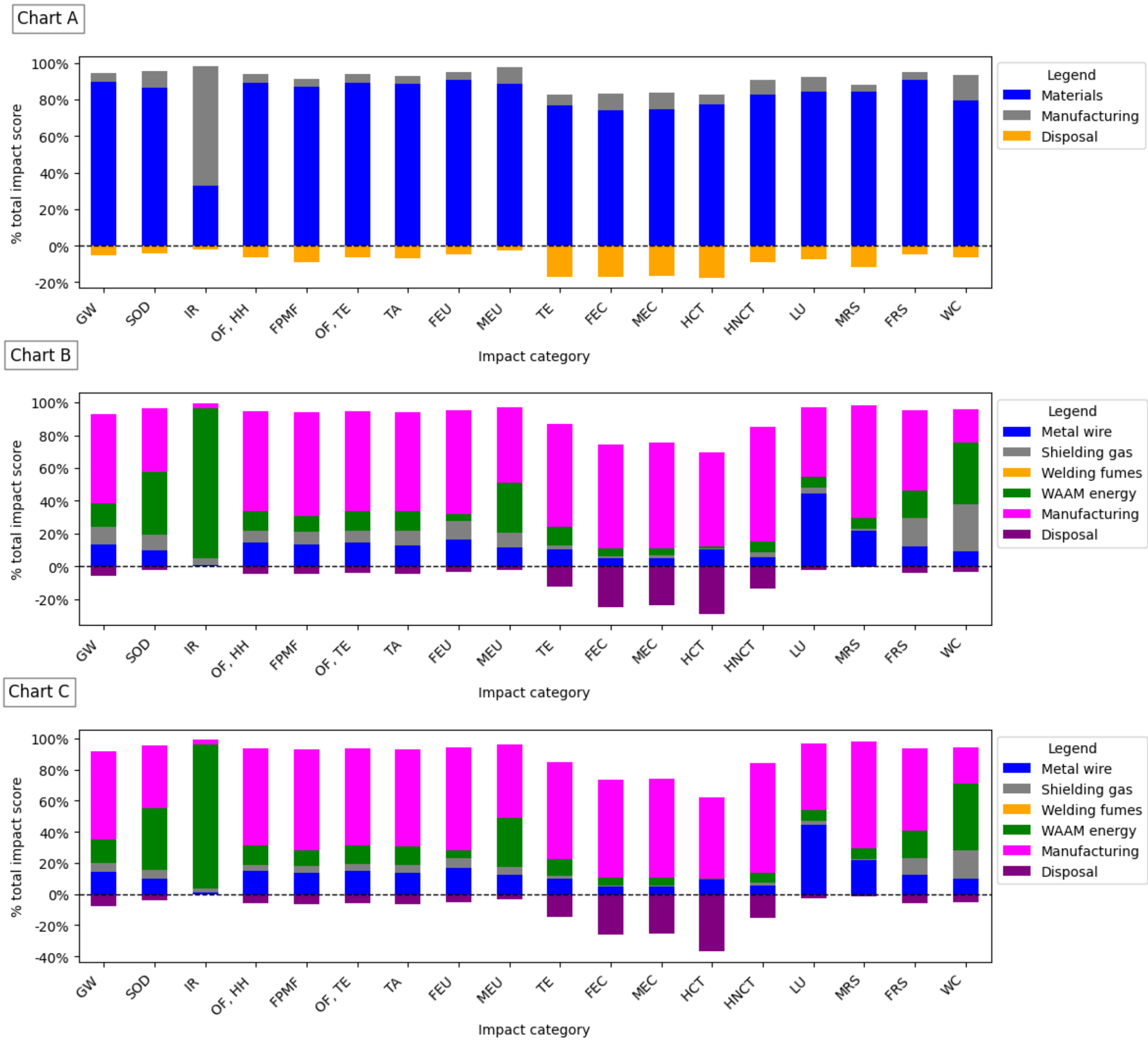



**Figure 22.** *Process contribution of Shapers injection mould (excluding the use stage) produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the use stage is the most contributing process except for Human cancerogenic toxicity and Mineral resource scarcity for which the materials are the most relevant process. For WAAM (i.e., (B) and (C)) the most contributing process is the manufacturing process (excluding consumables and metal wires but including the casted iron frame), except for Ionizing radiation, Marine eutrophication and Water consumption that are dominated by WAAM energy. While Land use is dominated by steel wires production and manufacturing. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.5.2 Life Cycle Costing (LCC)

**Table 20.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-3b.*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per mould (€) | Cost steel block (€) | |
| | Milling - total (€) | Milling - Manual labor (€/h) |
| | | Milling (h) |
| **Operational (use of injection mould)** | | |
| Energy consumption cost (€/product) | Energy cost (€/kWh) | |
| | Energy consumption (kWh/item lifetime use) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per mould (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **Operational (use of injection mould)** | | |
| Energy consumption cost (€/product) | Energy consumption cost (€/product) | |
| | Sold scrap from product machining (€/product) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

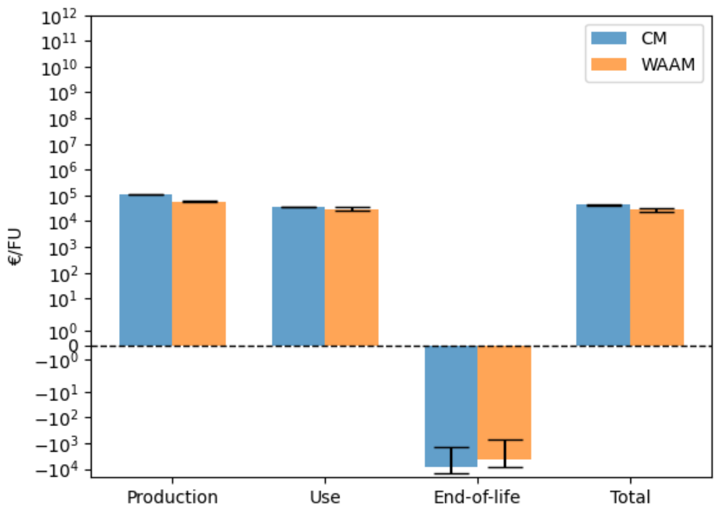



**Figure 23.** *illustration of financial life cycle cost of Shapers injection mould. Note: FU = functional unit.*

**Table 21.** *Comparison conventional and WAAM demonstrator B-3b.*

| | Production costs (€\FU) | Use stage costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|---|
| **Conventional injection mould** | 1.04E+05 | 3.43E+04 | 1.35E+03 to 1.52E+04 |
| **WAAM injection mould** | 5.43E+04 to 6.39E+04 | 2.57E+04 to 3.43E+04 | 7.40E+02 to 8.32E+03 |

## 3.6. Demonstrator B-4.1

This demonstrator is a cutting tool insert for automotive parts used by Gorenje Orodjarna. Wire Arc Additive Manufacturing (WAAM) will be used to produce it, instead of conventional manufacturing. The lead time can be potentially reduced to 1 week.

### 3.6.1 Life Cycle Assessment (LCA)

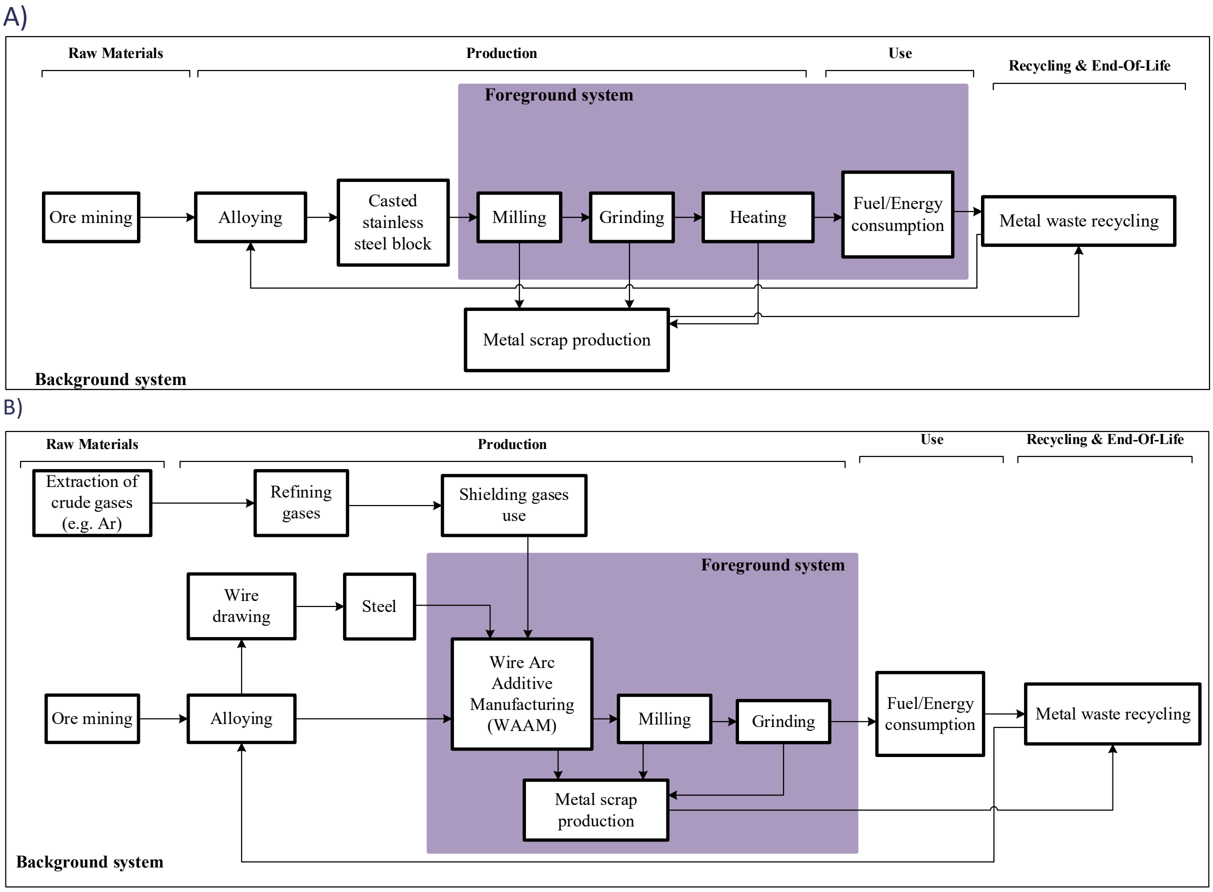



**Figure 24.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured Gorenje Orodjarna cutting tool demonstrator B-4.1. Note: MM-WAAM = multi-material wire arc additive manufacturing.*

**Table 22.** *Summary of scenario sensitivity analysis of Gorenje Orodjarna forming tool demonstrator B-4.1. Note that data and assumptions are based on the last meeting with the project partners on 28 - 06 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized shielding gas flow (15 L/min)<br>• Specific energy consumption low (kwh/kg deposited) | • Current shielding gas flow (20 L/min)<br>• Specific energy consumption high (kwh/kg deposited) |
| Use stage | | • | • |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 23.** *Characterized results B-4.1 ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 8.21E+02 | 4.49E+02 | 4.69E+02 |
| SOD [kg CFC11 eq] | 2.39E-04 | 1.36E-04 | 1.42E-04 |
| IR [kBq Co-60 eq] | 3.43E+01 | 3.63E+01 | 3.92E+01 |
| OF, HH [kg NOx eq] | 1.77E+00 | 9.51E-01 | 9.96E-01 |
| FPMF [kg PM2.5 eq] | 1.79E+00 | 8.48E-01 | 9.02E-01 |

| | | | |
|---|---|---|---|
| OF, TE [kg NOx eq] | 1.84E+00 | 9.91E-01 | 1.04E+00 |
| TA [kg SO2 eq] | 2.42E+00 | 1.25E+00 | 1.32E+00 |
| FEU [kg P eq] | 3.64E-01 | 2.37E-01 | 2.48E-01 |
| MEU [kg N eq] | 5.97E-02 | 3.82E-02 | 3.95E-02 |
| TE [kg 1,4-DCB] | 8.41E+03 | 3.17E+03 | 3.49E+03 |
| FEC [kg 1,4-DCB] | 4.70E+01 | 2.37E+01 | 2.59E+01 |
| MEC [kg 1,4-DCB] | 6.62E+01 | 3.30E+01 | 3.59E+01 |
| HCT [kg 1,4-DCB] | 4.24E+02 | 1.80E+02 | 1.99E+02 |
| HNCT [kg 1,4-DCB] | 1.81E+02 | 4.77E+02 | 5.06E+02 |
| LU [m2a crop eq] | 2.06E+01 | 2.15E+01 | 2.21E+01 |
| MRS [kg Cu eq] | 3.70E+01 | 1.56E+01 | 1.68E+01 |
| FRS [kg oil eq] | 2.06E+02 | 1.16E+02 | 1.22E+02 |
| WC [m3] | 2.50E+02 | 6.98E+00 | 8.16E+00 |

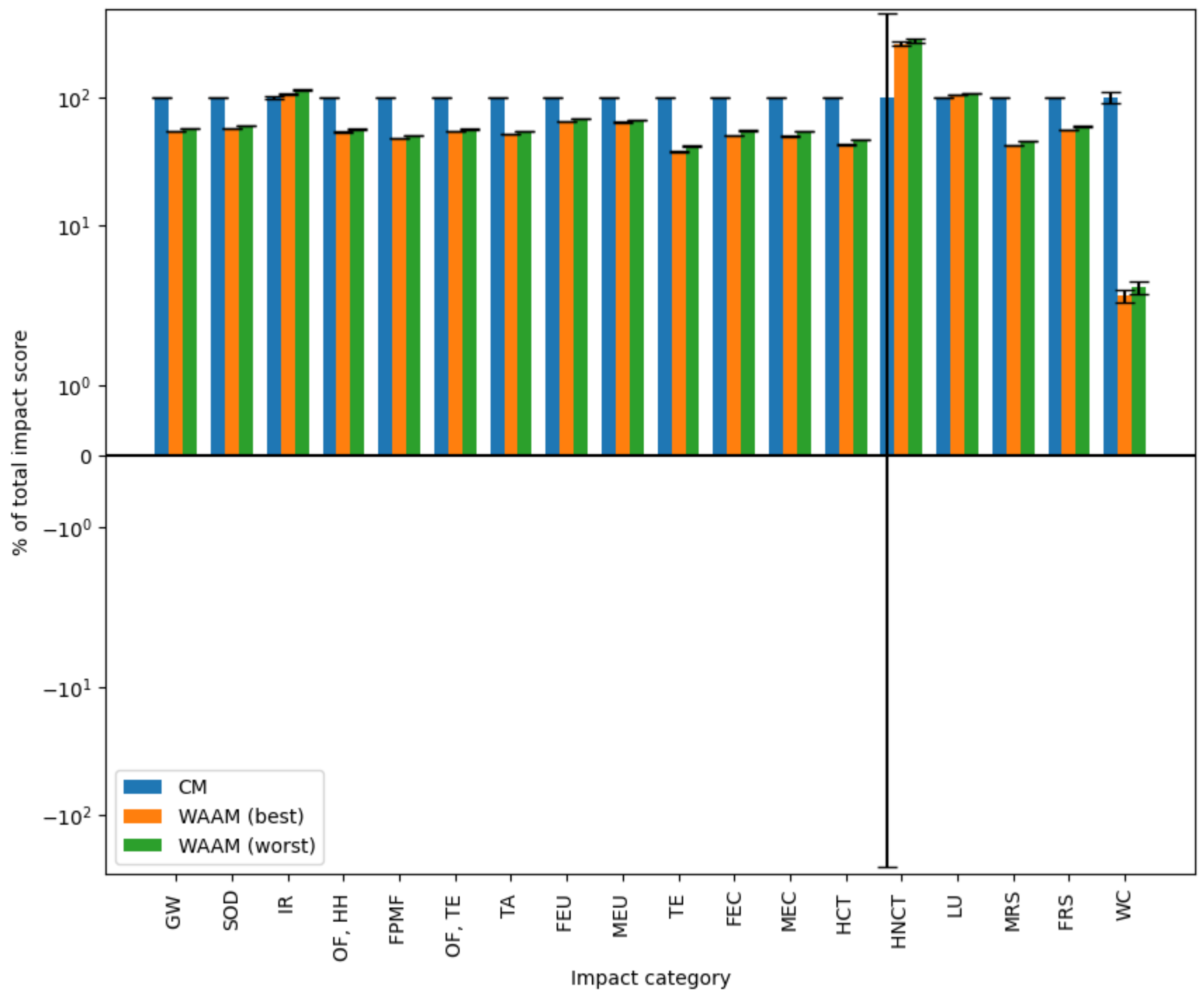



**Figure 25.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-4.1 with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) and WAAM (worst) in 15 out of 18 impact categories. Y-axis is in logarithmic scale.*

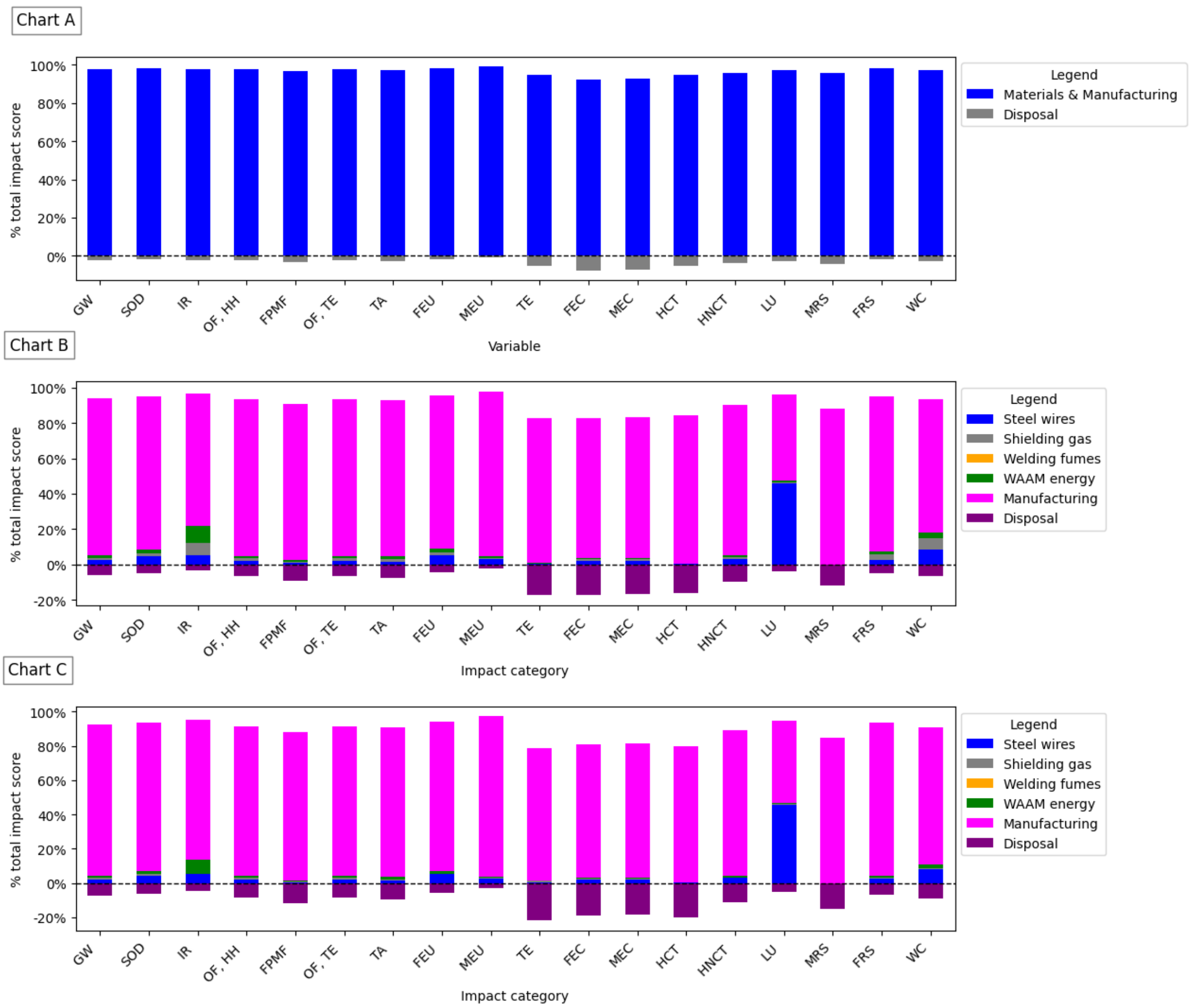



**Figure 26.** *Process contribution of Gorenje Orodjarna demonstrator B-4.1 produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the materials&manufacturing life cycle stage is the most contributing process. The major difference between WAAM (best) and WAAM (worst) is the contribution of shielding gas to the total impact score which appears in Ionizing radiation and Water consumptions categories when WAAM (worst) is considered. The most contributing process in manufacturing except for Land use that is the steel wire production. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.6.2 Life Cycle Costing (LCC)

**Table 24.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-4.1.*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per cutting tool (€) | | Cost steel block (€) |
| | Milling - total (€) | Milling - Manual labor (€/h) |
| | | Milling (h) |
| **Operational (use of cutting tool)** | | |
| Repair (€/yr) | | Repair cost (€/product) |
| | | Repair time (n./yr) |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | | Recycling disposed product (kg/product) |
| | | Sold scrap from product machining (€/kg) |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per cutting tool (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

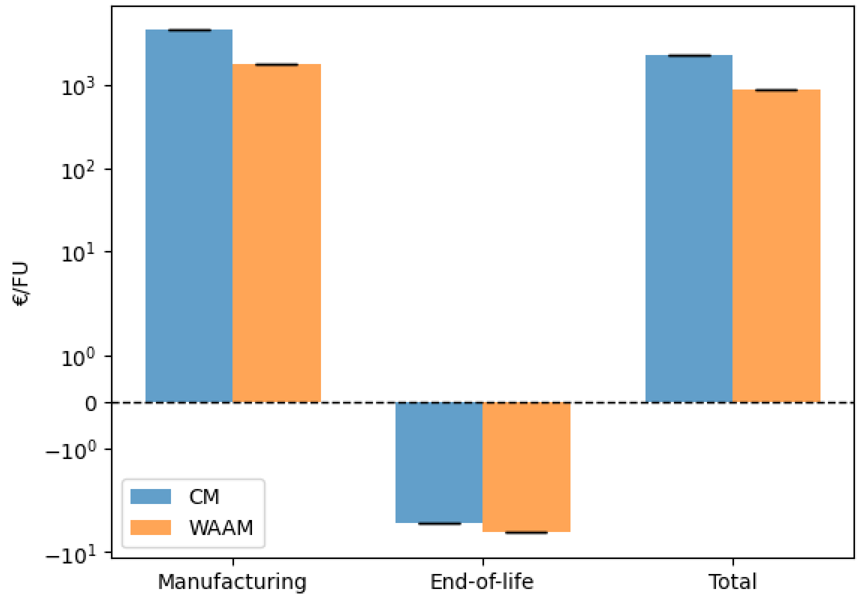



**Figure 27.** *Illustration of financial life cycle cost of Gorenje Orodjarna demonstrator B-4.1. Note: FU = functional unit.*

**Table 25.** *Comparison between conventional and WAAM demonstrator B-3b.*

| | Production costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|
| **Conventional cutting tool** | 4.53E+03 | 4.49E+00 |
| **WAAM cutting tool** | 1.76E+03 | 5.85E+00 |

## 3.7. Demonstrator B-4.2

This demonstrator is a forming tool insert for automotive parts used by Gorenje Orodjarna. Wire Arc Additive Manufacturing (WAAM) will be used for the production of it, instead of conventional manufacturing.

The lead time can be potentially reduced to 1 week.

### 3.7.1 Life Cycle Assessment (LCA)

A)

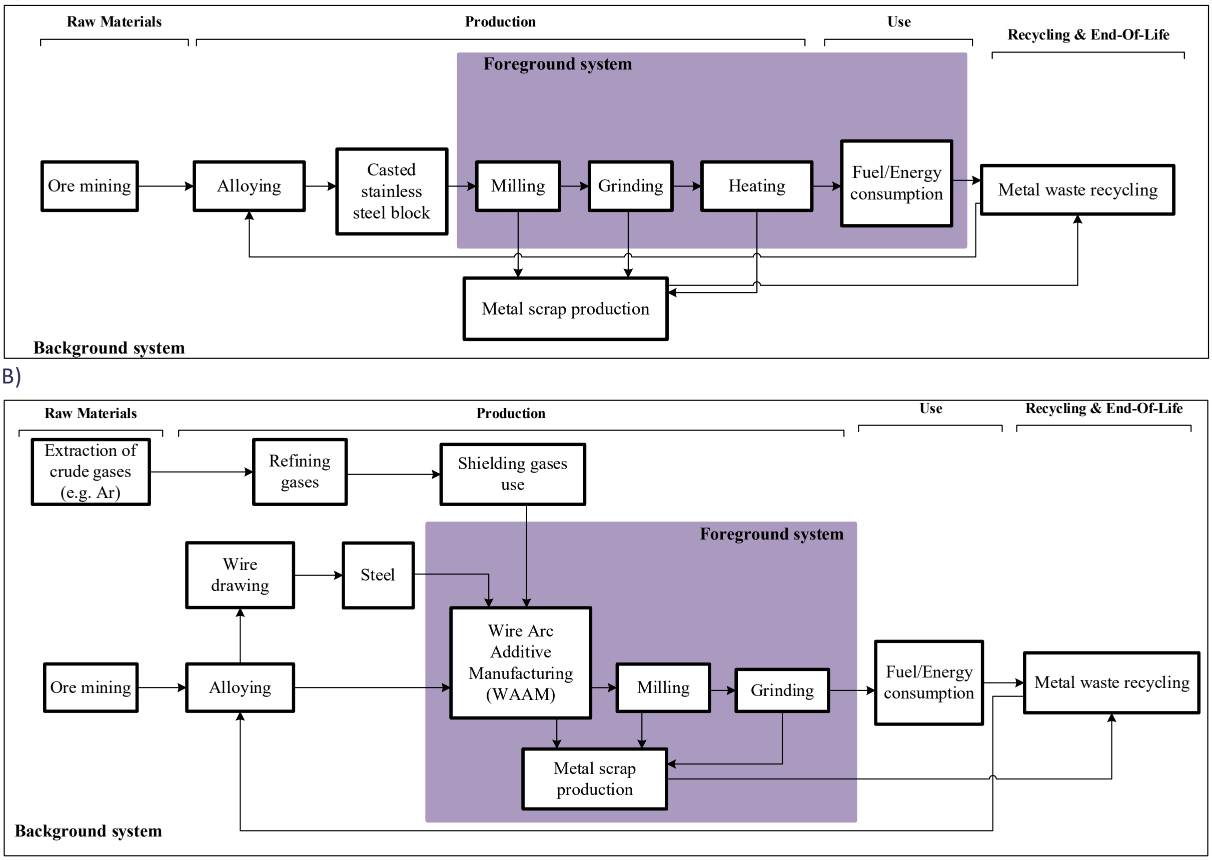



**Figure 28.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured Gorenje Orodjarna forming tool demonstrator B-4.2. Note: MM-WAAM = multi-material wire arc additive manufacturing.*

**Table 26.** *Summary of scenario sensitivity analysis of Gorenje Orodjarna forming tool demonstrator B-4.2. Note that data and assumptions are based on the last meeting with the project partners on 28 - 06 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized shielding gas flow (15 L/min)<br>• Specific energy consumption low (kwh/kg deposited) | • Current shielding gas flow (20 L/min)<br>• Specific energy consumption high (kwh/kg deposited) |
| Use stage | | • | • |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 27.** *Characterized results B-4.2 ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 3.78E+03 | 2.30E+03 | 2.41E+03 |
| SOD [kg CFC11 eq] | 1.11E-03 | 6.96E-04 | 7.26E-04 |
| IR [kBq Co-60 eq] | 1.45E+02 | 1.84E+02 | 2.00E+02 |
| OF, HH [kg NOx eq] | 8.24E+00 | 4.92E+00 | 5.16E+00 |
| FPMF [kg PM2.5 eq] | 8.42E+00 | 4.40E+00 | 4.66E+00 |
| OF, TE [kg NOx eq] | 8.58E+00 | 5.11E+00 | 5.39E+00 |

| | | | |
|---|---|---|---|
| TA [kg SO2 eq] | 1.13E+01 | 6.44E+00 | 6.78E+00 |
| FEU [kg P eq] | 1.68E+00 | 1.19E+00 | 1.25E+00 |
| MEU [kg N eq] | 2.71E-01 | 1.90E-01 | 1.97E-01 |
| TE [kg 1,4-DCB] | 3.81E+04 | 1.65E+04 | 1.82E+04 |
| FEC [kg 1,4-DCB] | 2.02E+02 | 1.24E+02 | 1.31E+02 |
| MEC [kg 1,4-DCB] | 2.82E+02 | 1.72E+02 | 1.82E+02 |
| HCT [kg 1,4-DCB] | 2.01E+03 | 9.71E+02 | 1.07E+03 |
| HNCT [kg 1,4-DCB] | 2.77E+02 | 3.04E+03 | 2.60E+03 |
| LU [m2a crop eq] | 9.49E+01 | 1.01E+02 | 1.05E+02 |
| MRS [kg Cu eq] | 1.71E+02 | 8.23E+01 | 8.80E+01 |
| FRS [kg oil eq] | 9.50E+02 | 5.91E+02 | 6.27E+02 |
| WC [m3] | 6.01E+02 | 4.23E+01 | 5.02E+01 |

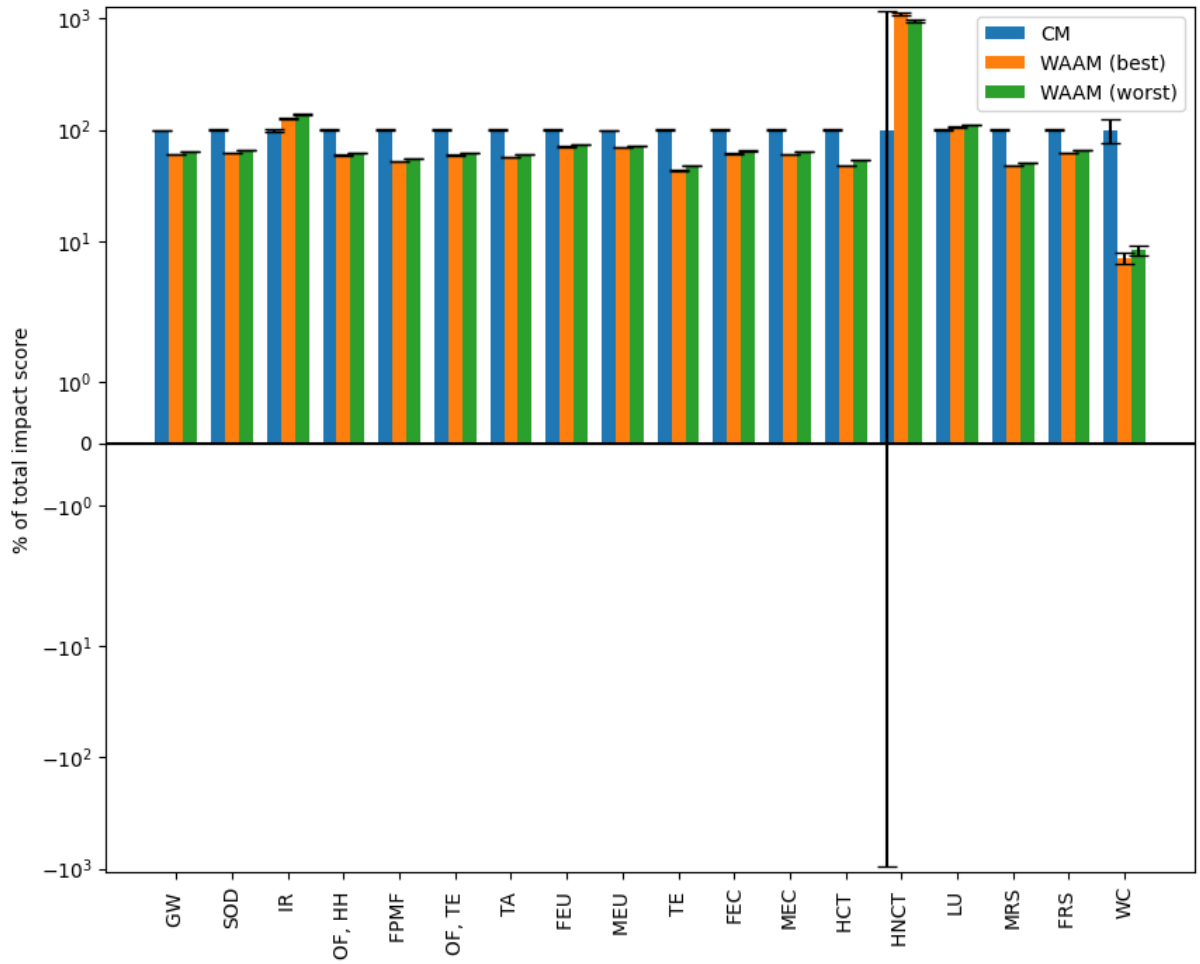



**Figure 29.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-4.2 with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) an WAAM (worst) in 15 out of 18 impact categories. Y-axis in logarithmic scale.*

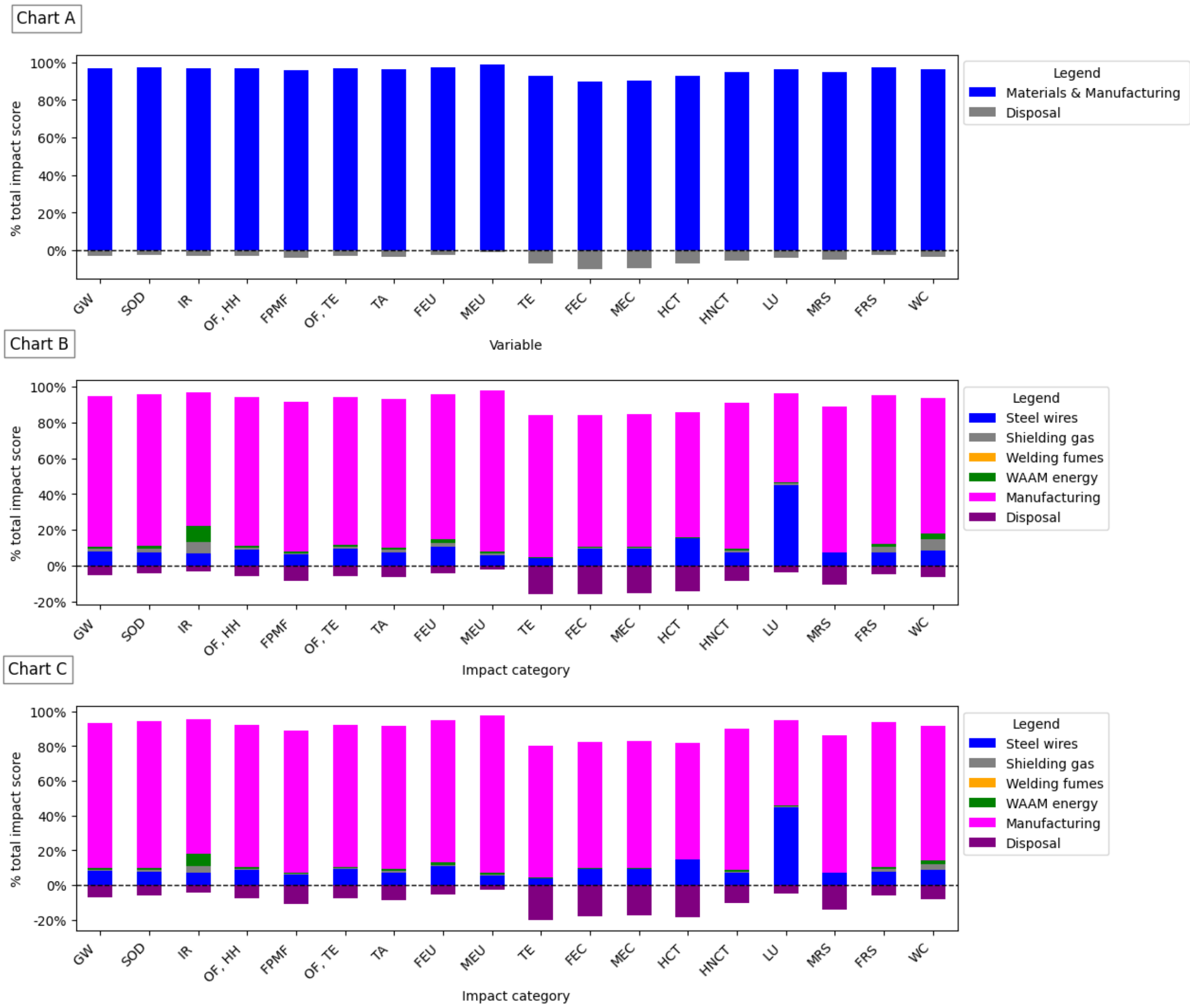



**Figure 30.** *Process contribution of Gorenje Orodjarna demonstrator B-4.2 produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the materials & manufacturing life cycle stage is the most contributing process. There are no evident differences between WAAM (best) and WAAM (worst). The most contributing process in manufacturing except for Land use that is the steel wire production. The major difference between WAAM (best) and WAAM (worst) is the contribution of shielding gas to the total impact score which appears in Ionizing radiation and Water consumptions categories when WAAM (worst) is considered. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.7.2 Life Cycle Costing (LCC)

**Table 28.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-4.2*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per forming tool (€) | | Cost steel block (€) |
| | Milling - total (€) | Milling - Manual labor (€/h) |
| | | Milling (h) |
| **Operational (use of cutting tool)** | | |
| Repair (€/yr) | | Repair cost (€/product) |
| | | Repair time (n./yr) |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | | Recycling disposed product (kg/product) |
| | | Sold scrap from product machining (€/kg) |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per forming tool (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

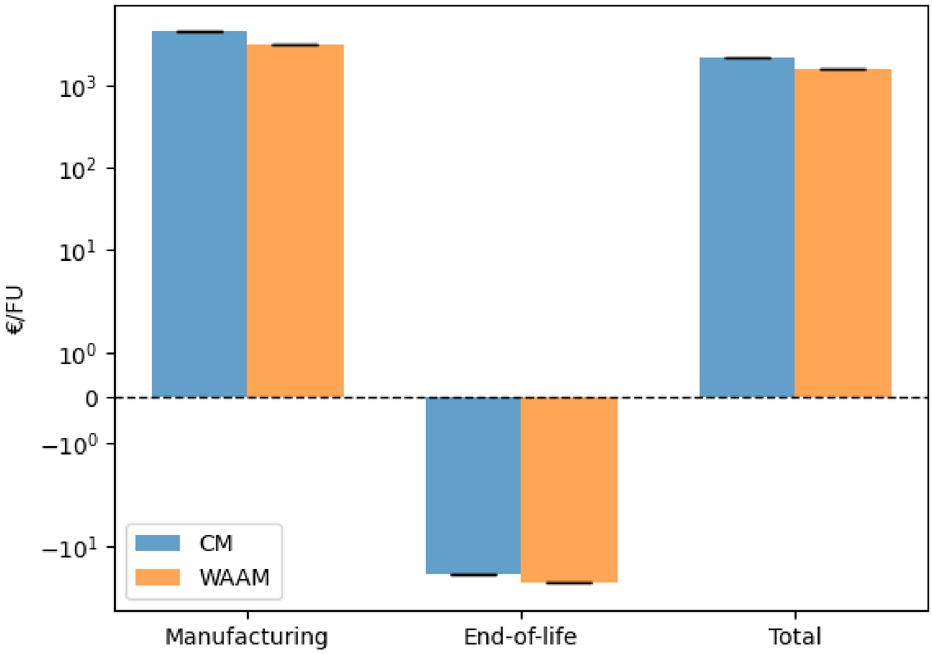



**Figure 31.** *Illustration of financial life cycle cost of Gorenje Orodjarna demonstrator B-4.2. Note: FU = functional unit.*

**Table 29.** *Comparison conventional and WAAM demonstrator B-5.*

| | Production costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|
| **Conventional cutting tool** | 4.37E+03 | 2.17E+01 |
| **WAAM cutting tool** | 3.13E+03 | 2.80E+01 |

## 3.8. Demonstrator B-5

This demonstrator is a forming die for white goods (i.e. back face of washing machine drum) used by Gorenje Orodjarna. Wire Arc Additive Manufacturing (WAAM) will be used for the production of it, instead of conventional manufacturing. This material was deemed unsuitable for automatic repair. A special bronze alloy, chosen for its tribological properties in metal forming, is used instead. The alloy is sensitive to heat fluctuations and requires consistent, high preheating. Therefore, process stability

and control are critical during deposition, with careful management of interpass temperatures. Long continuous beads are not recommended, as they prevent necessary pauses to regulate heat. Additionally, due to the material's sensitivity to cracking, cooling with liquid nitrogen is not advisable. Use of the forming die is the same, thus it was disregarded from the analysis. However, repairs of it was included as it may be different.
Lead time is estimated to be potentially reduced by about 39% to 83% with WAAM.

### 3.8.1 Life Cycle Assessment (LCA)

A)

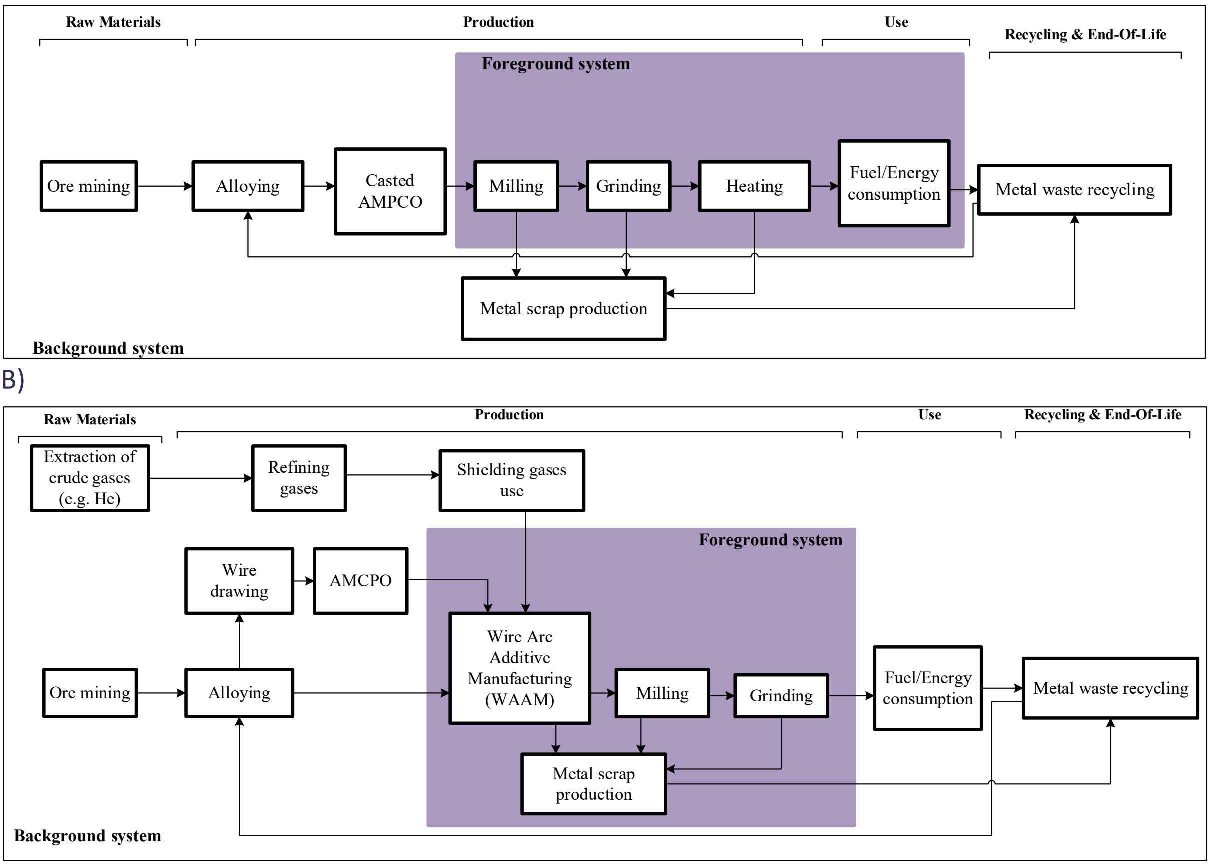



**Figure 32.** *System boundaries of life cycle of A) conventionally manufactured, and B) additively manufactured Gorenje Orodjarna forming tool demonstrator B-5. Note: MM-WAAM = multi-material wire arc additive manufacturing.*

**Table 30.** *Summary of scenario sensitivity analysis of Gorenje Orodjarna forming tool demonstrator B-5. Note that data and assumptions are based on the last meeting with the project partners on 28 - 06 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Manufacturing stage | WAAM | • Optimized shielding gas flow (15 L/min) | • Current shielding gas flow (20 L/min) |
| Use stage | | • Repair every two months with 1 kg added via WAAM | • Repair every month with 2 kg added via WAAM |
| End-Of-Life | | • | • |

**Table 31.** *Characterized results B-5 ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 1.86E+01 | 2.91E+00 | 1.25E+01 |
| SOD [kg CFC11 eq] | 4.94E+02 | 1.46E+02 | 3.12E+02 |
| IR [kBq Co-60 eq] | 4.58E+03 | 6.10E+02 | 3.14E+03 |
| OF, HH [kg NOx eq] | 5.91E+00 | 9.48E-01 | 4.12E+00 |
| FPMF [kg PM2.5 eq] | 1.90E+03 | 5.38E+02 | 1.17E+03 |
| OF, TE [kg NOx eq] | 5.43E+02 | 3.17E+02 | 6.35E+02 |
| TA [kg SO2 eq] | 7.19E+04 | 9.35E+03 | 4.76E+04 |
| FEU [kg P eq] | 1.13E+02 | 5.91E+01 | 1.38E+02 |
| MEU [kg N eq] | 2.89E+02 | 7.65E+01 | 1.62E+02 |
| TE [kg 1,4-DCB] | 5.86E+03 | 7.83E+02 | 4.01E+03 |
| FEC [kg 1,4-DCB] | 1.58E-01 | 3.65E-02 | 9.02E-02 |
| MEC [kg 1,4-DCB] | 2.57E+02 | 4.31E+01 | 1.86E+02 |
| HCT [kg 1,4-DCB] | 1.23E+01 | 2.15E+00 | 7.15E+00 |
| HNCT [kg 1,4-DCB] | 1.26E+01 | 2.24E+00 | 7.35E+00 |
| LU [m2a crop eq] | 1.29E-03 | 2.67E-04 | 8.91E-04 |
| MRS [kg Cu eq] | 5.44E+01 | 7.82E+00 | 3.63E+01 |
| FRS [kg oil eq] | 4.13E+05 | 5.46E+04 | 2.83E+05 |
| WC [m3] | 2.60E+01 | 3.63E+01 | 6.24E+01 |

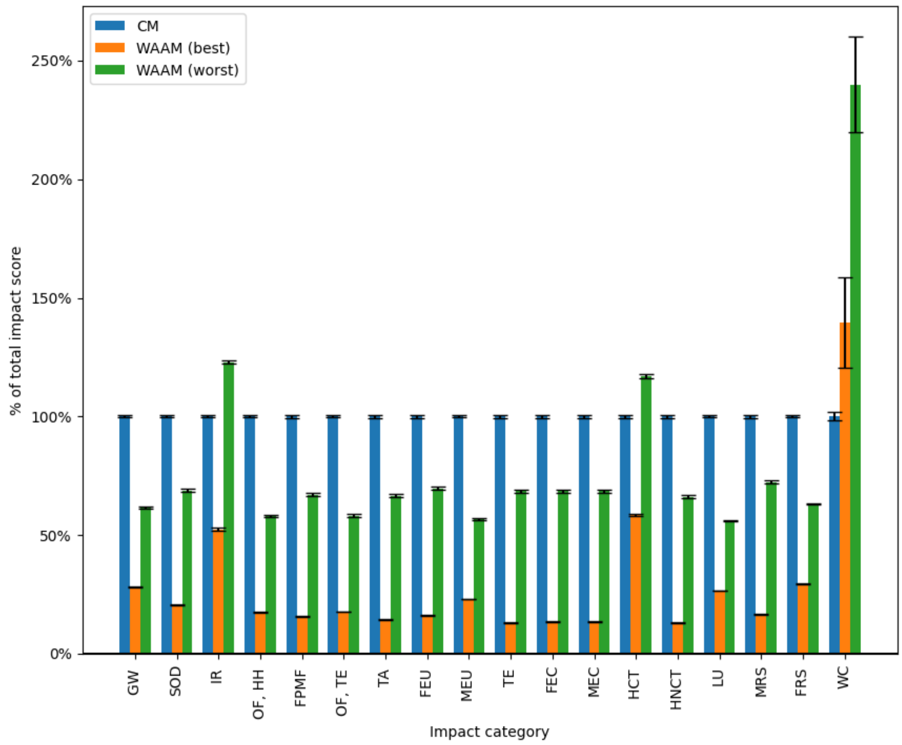



**Figure 33.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-5 with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) in 17 out of 18 impact categories, and is also worse than WAAM (worst) in 15 out of 18 impact categories.*

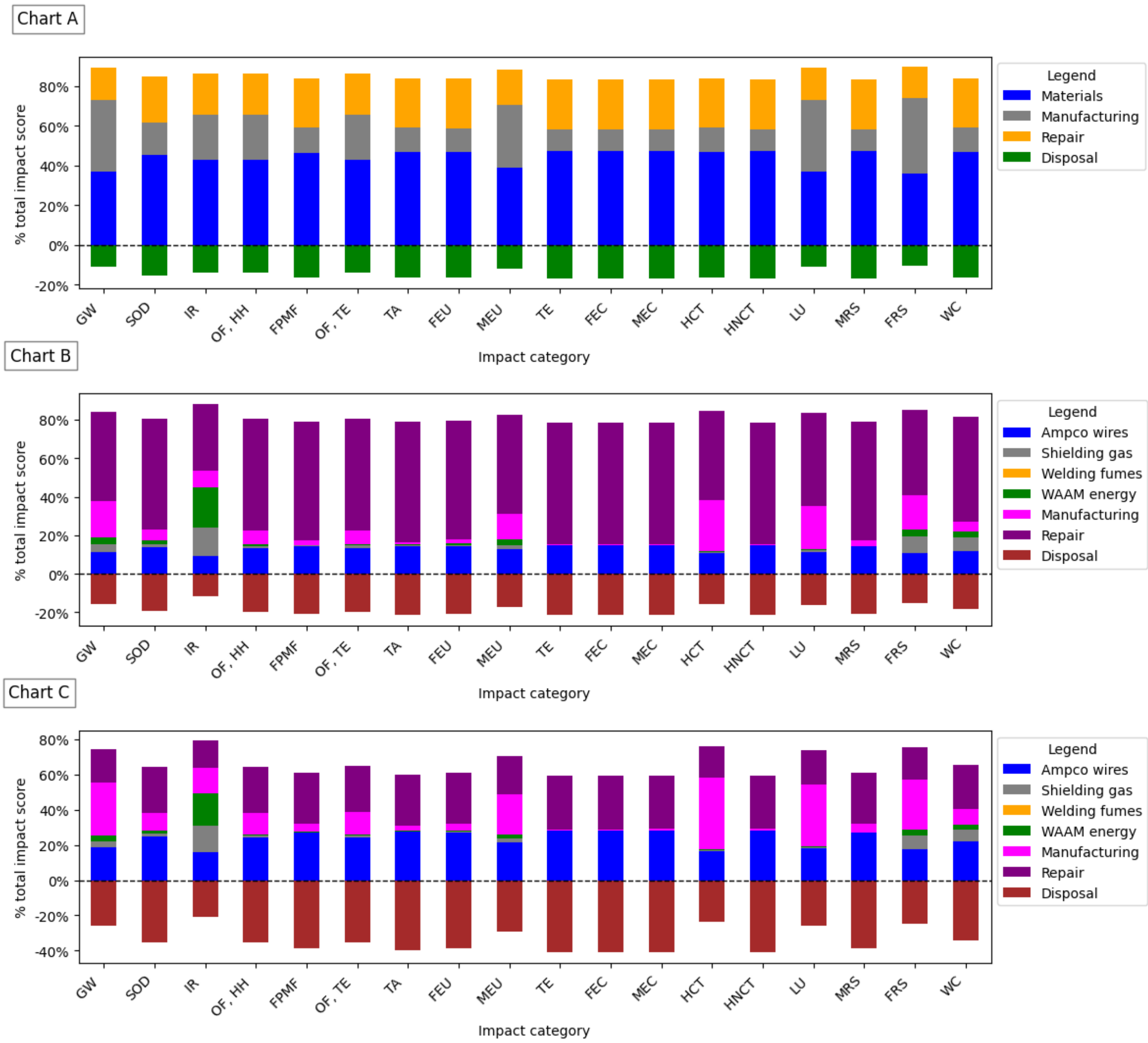



**Figure 34.** *Process contribution of Gorenje Orodjarna forming tool demonstrator B-5 produced with (A) conventional manufacturing; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the materials life cycle stage is the most contributing process except for Global Warming, Marine Eutrophication, Fossil resource scarcity and Land use for which the manufacturing (including casting, milling and transportation) is the most relevant life cycle stage. The biggest difference between WAAM (best) and WAAM (worst) is the extent of contribution to the total impact score by the repair during the tool use which is much larger for the latter scenario. Apart from the repair during the use stage, the most contributing process is the metal wire production and manufacturing stage. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.8.2 Life Cycle Costing (LCC)

**Table 32.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-5.*

| CM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per cutting tool (€) | Cost steel block (€) | |
| | Milling - total (€) | Milling - Manual labor (€/h) |
| | | Milling (h) |
| **Operational (use of cutting tool)** | | |
| Repair (€/yr) | Repair cost (€/product) | |
| | Repair time (n./yr) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

| WAAM | | |
|---|---|---|
| **COSTS** | | |
| **Manufacturing** | | |
| Total cost per cutting tool (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) |
| | | Software cost (€/year) |
| | | Maintenance cost (€/year) |
| | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) |
| | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | |
| **Operational (use of cutting tool)** | | |
| Repair (€/yr) | Repair cost (€/product) | |
| | Repair time (n./yr) | |
| **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | |

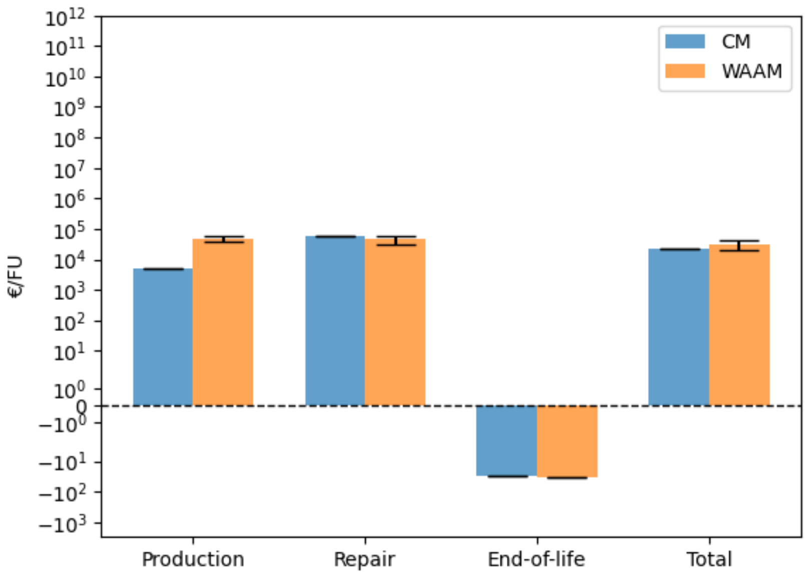



**Figure 35.** *Illustration of financial life cycle cost of Gorenje Orodjarna forming tool. Note: FU = functional unit.*

**Table 33.** *Comparison between conventional and WAAM demonstrator B-5.*

| | Production costs (€\FU) | Repair costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|---|
| **Conventional forming die** | 5.19E+03 | 6.05E+04 | 3.16E+01 |
| **WAAM forming die** | 3.74E+04 to 5.96E+04 | 3.03E+04 to 6.05E+04 | 3.23E+01 |

## 3.9. Demonstrator B-6

This demonstrator is a hot forging die used by Kuznia and it requires frequent repairs. Wire Arc Additive Manufacturing (WAAM) will be used for repair purpose instead of conventional welding. Note that the current repair practice uses the same technology (gas metal arc welding). We assumed that WAAM forging die repair is once every two months due (instead of once a month as for the conventionally

manufactured forging die). Similar wear friction coefficient and hardness (approx. 40 HRC at about 500 Celsius) to conventionally repaired forging die. Tested for 3,000 pieces production in Kuznia.
The lead time is estimated to be reduced by 61% in comparison to the current practice.

### 3.9.1 Life Cycle Assessment (LCA)

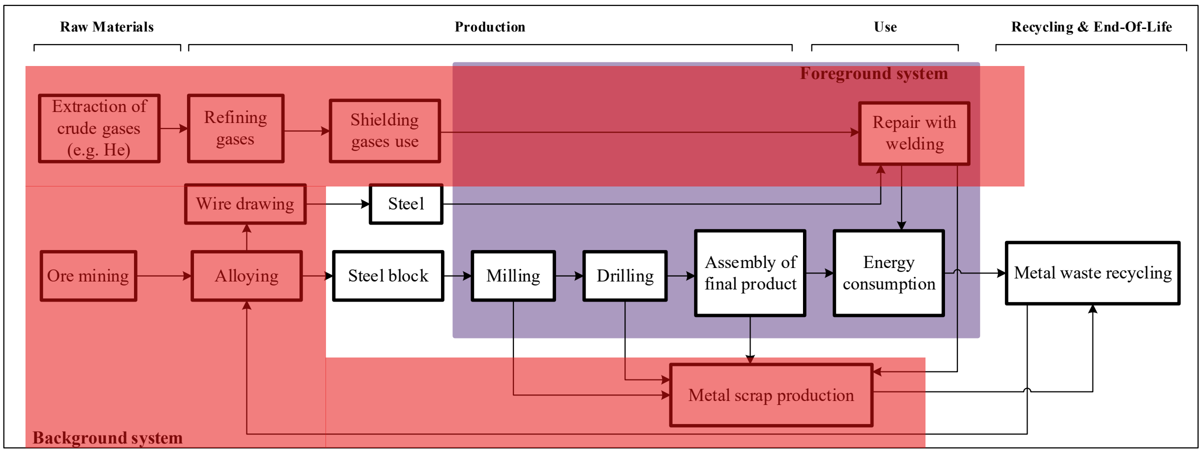



**Figure 36.** *System boundaries of life cycle of conventional manufacturing and wire arc additive manufacturing of Kuznia Jawor hot forging die (repair case). The part highlighted in red includes the processes considered in the LCA-model, since all the others are the same.*

**Table 34.** *Summary of scenario sensitivity analysis of Kuznia forging die. Note that data and assumptions are based on the last meeting with the project partners on 22 - 10 - 2024.*

| LC-stage | Manufacturing type | Best scenario | Worst scenario |
|---|---|---|---|
| Repair stage | WAAM | • Optimized shielding gas flow (15 L/min)<br>• Repair of the forging die with WAAM every two months<br>• Rockwool used 12 times a year | • Current shielding gas flow (20 L/min)<br>• Repair of the forging die with WAAM every month as for conventionally repaired forging die<br>• Rockwool used 6 times a year |
| End-Of-Life | | • Recycling rate based on discarded products from the literature [4], [5] varied of -25% | • Recycling rate based on discarded products from the literature [4], [5] |

**Table 35.** *Characterized results B-6 ReCiPe2016 (H) midpoint including best and worst scenario for WAAM and Monte Carlo analysis results (here median results are reported).*

| Impact category and unit | CM | WAAM (best) | WAAM (worst) |
|---|---|---|---|
| GW [kg CO2 eq] | 5.87E+03 | 1.41E+03 | 7.37E+03 |
| SOD [kg CFC11 eq] | 1.31E-03 | 3.21E-04 | 1.56E-03 |
| IR [kBq Co-60 eq] | 1.80E+02 | 2.83E+01 | 1.47E+02 |
| OF, HH [kg NOx eq] | 1.28E+01 | 3.15E+00 | 1.58E+01 |
| FPMF [kg PM2.5 eq] | 1.20E+01 | 2.84E+00 | 1.42E+01 |
| OF, TE [kg NOx eq] | 1.32E+01 | 3.26E+00 | 1.62E+01 |
| TA [kg SO2 eq] | 3.30E+01 | 5.88E+00 | 3.31E+01 |
| FEU [kg P eq] | 5.94E+00 | 1.08E+00 | 6.52E+00 |
| MEU [kg N eq] | 4.10E-01 | 8.39E-02 | 4.79E-01 |
| TE [kg 1,4-DCB] | 5.42E+04 | 7.87E+03 | 3.30E+04 |
| FEC [kg 1,4-DCB] | 6.75E+02 | 1.49E+01 | 1.59E+02 |
| MEC [kg 1,4-DCB] | 8.94E+02 | 3.12E+01 | 2.43E+02 |
| HCT [kg 1,4-DCB] | 4.20E+02 | 5.75E+02 | 2.44E+03 |

| | | | |
|---|---|---|---|
| HNCT [kg 1,4-DCB] | 1.49E+04 | 2.90E+03 | 1.26E+04 |
| LU [m2a crop eq] | 1.24E+02 | 1.02E+02 | 3.68E+02 |
| MRS [kg Cu eq] | 6.83E+01 | 4.01E+01 | 1.34E+02 |
| FRS [kg oil eq] | 1.41E+03 | 3.41E+02 | 1.77E+03 |
| WC [m3] | 3.28E+02 | 3.95E+02 | 1.10E+03 |

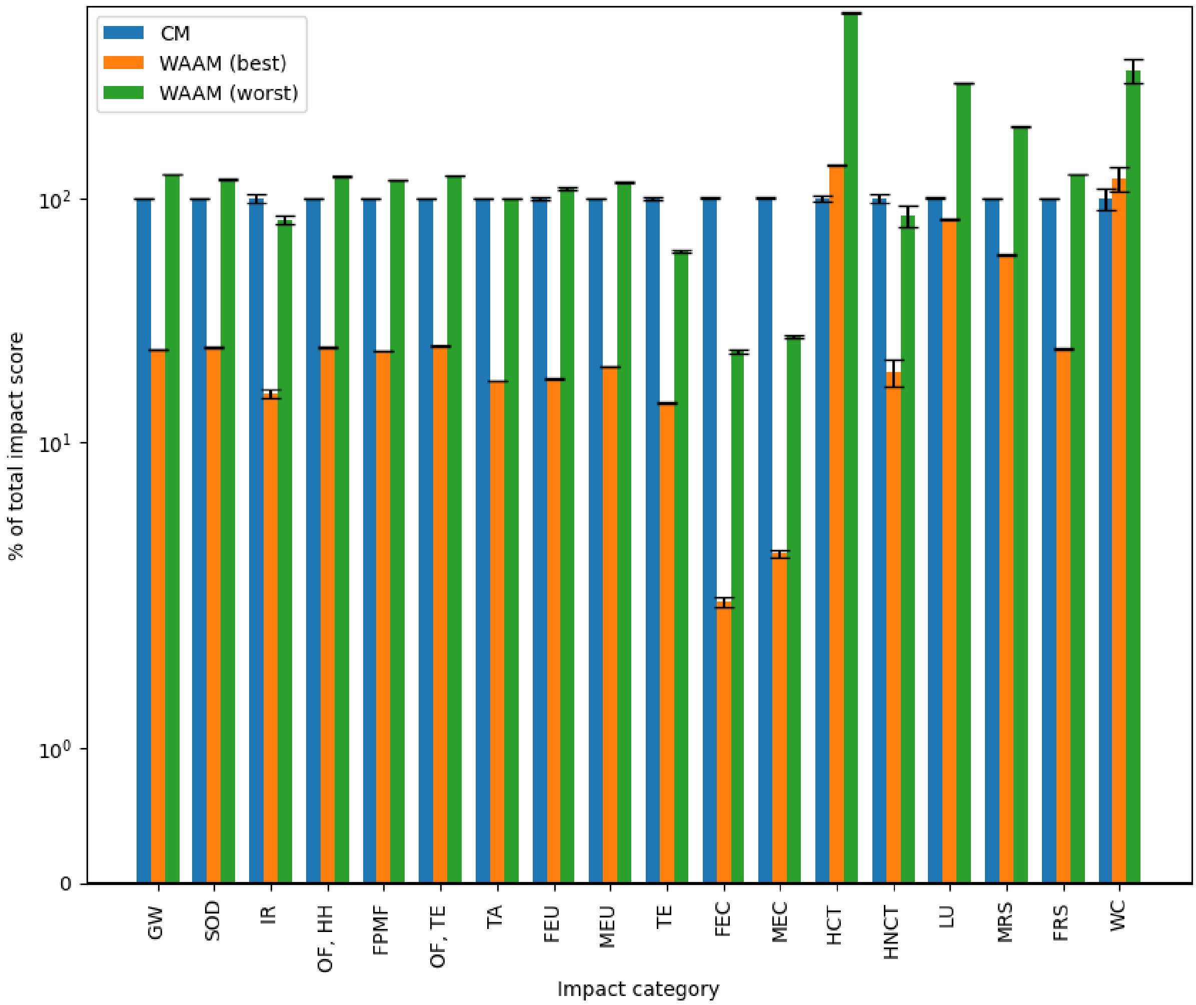



**Figure 37.** *Internally normalized results calculated with ReCiPe2016 (H) for demonstrator B-6 with uncertainty calculated with Monte Carlo analysis for model parameters. Conventional manufacturing (CM) is worse than WAAM (best) in 16 out of 18 impact categories, while is better than WAAM (worst) in 13 out of 18 impact categories. Y-axis is in logscale.*

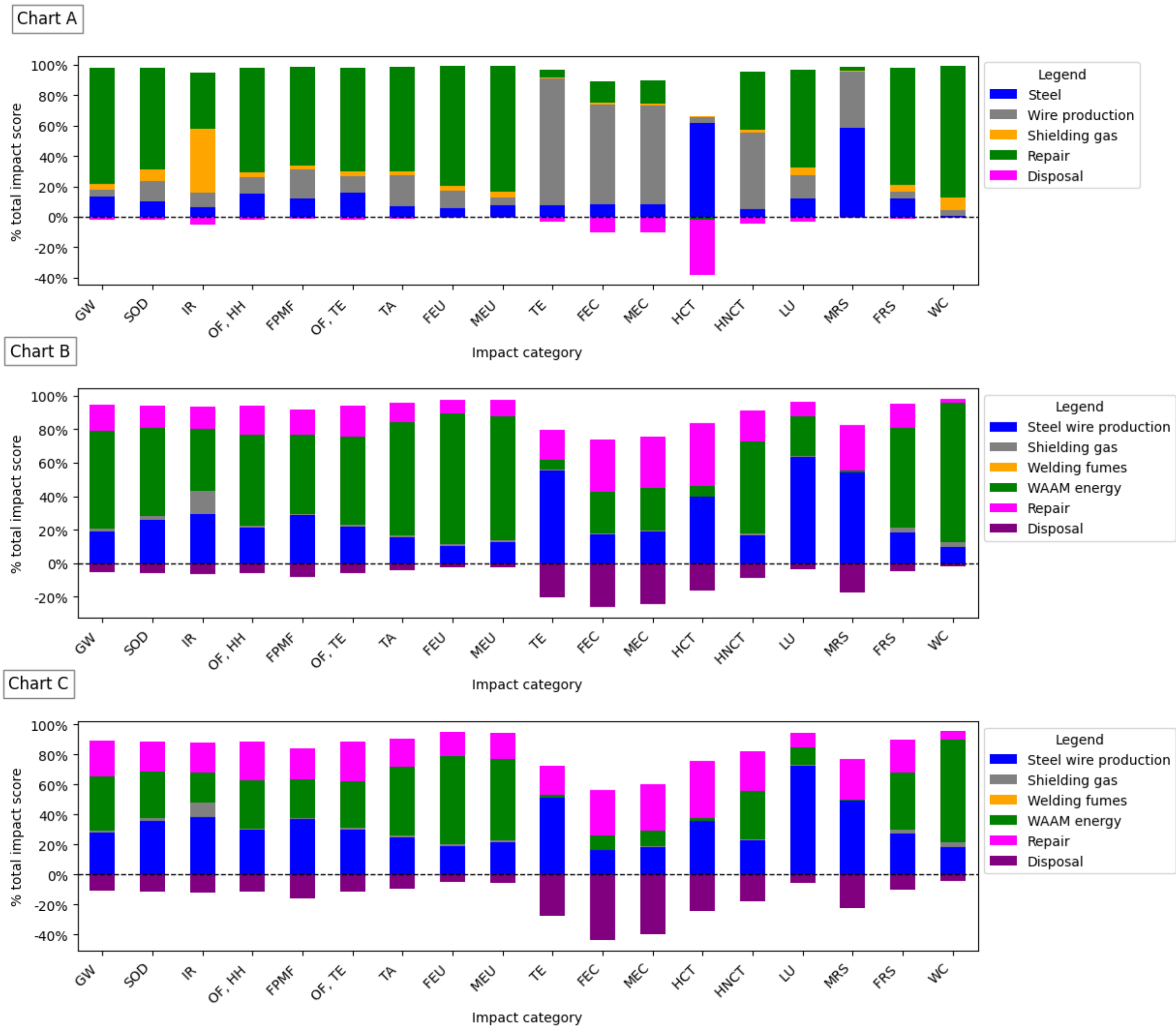



**Figure 38.** *Process contribution of Kuznia forging die repair with (A) conventional welding; (B) WAAM (worst) and (C) WAAM (best). By looking at (A) the most contributing process is repair (including transportation and electricity use), followed by the wire production process. For WAAM (best) and (worst) the most contributing process is energy consumption for manufacturing (WAAM Energy). Between the two scenarios there is not much difference as the frequency of repair of the forging die with WAAM. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. This is based on characterized results calculated with ReCiPe2016 (H) without Monte Carlo analysis.*

### 3.9.2 Life Cycle Costing (LCC)

**Table 36.** *Inventory of costs/revenues throughout the whole life cycle of demonstrator B-6.*

| CM | | | WAAM | | |
|---|---|---|---|---|---|
| **COSTS** | | | **COSTS** | | |
| **Operational (maintenance of forging die)** | | | **Operational (maintenance of forging die)** | | |
| Total cost per hot forging die repaired (€) | Welding machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) | Total cost per hot forging die repaired (€) | WAAM machine use cost (staff full time present) (€/item) | Rent of building and equipment (€/year) |
| | | Operator hourly rate (€/h) | | | Operator hourly rate (€/h) |
| | | Software cost (€/year) | | | Software cost (€/year) |
| | | Maintenance cost (€/year) | | | Maintenance cost (€/year) |
| | | Welding machine total hourly rate (operator present) (€/h) | | | WAAM machine total hourly rate (operator present) (€/h) |
| | | Time for deposition (h) | | | Time for deposition (h) |
| | Welding wire cost (€/item) | | | Welding wire cost (€/item) | |
| | Welding consumables cost (gas and power) (€/item) | | | Welding consumables cost (gas and power) (€/item) | |
| | Machining/finishing cost (€/h) | | | Machining/finishing cost (€/h) | |
| **REVENUE-RECYCLABLES** | | | **REVENUE-RECYCLABLES** | | |
| Recycling - Scrapping value (€/product) | Recycling disposed product (kg/product) | | Recycling - Scrapping value (€/**product**) | Recycling disposed product (kg/product) | |
| | Sold scrap from product machining (€/kg) | | | Sold scrap from product machining (€/kg) | |

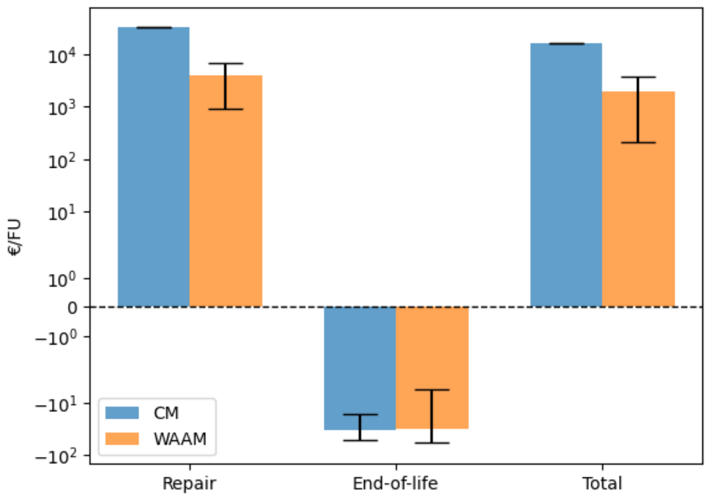



**Figure 39.** *Illustration of financial life cycle cost of Kuznia Jawor hot forging die repair. Note: FU = functional unit.*

**Table 37**. *Comparison between conventional and WAAM demonstrator B-6.*

| | Repair costs (€\FU) | Revenue-recyclables (€\FU) |
|---|---|---|
| **Conventional injection mould** | 3.12E+04 | 1.66E+01 to 5.17E+01 |
| **WAAM injection mould** | 9.08E+02 to 6.18E+03 | 5.55E+00 to 5.94E+01 |

# 4 Interpretation

Performing a "reality check" is an essential step to ensure the credibility and accuracy of the assessment findings. Several steps were taken into consideration, including data completeness and consistency check, comparison with existing knowledge, and sensitivity analysis (see chapter **Error! Reference source not found.**).

## 4.1. Completeness and consistency check

The table below presents an overview of the data availability and what sources we used for each data category. Additionally, it should be mentioned that we disregarded any data relative to electricity use for pre- or post-heating during WAAM manufacturing which is an important step for several demonstrators, namely A-1 (for Inconel625), A-2b, B-2, B-4, B-5 and B-6. This was due to the lack of specific energy consumption data, and it was systematically excluded from the manufacturing analysis.

**Table 38.** *WAAM equipment and printed demonstrator data are primary and estimated.*

| Demonstrator | Life Cycle stage | % data availability (CM) | Origin of data | % data availability (WAAM) | Origin of data |
|---|---|---|---|---|---|
| A-1, A-2b, B-1, B-2, B-3b, B-4.1, B-4.2, B-5, B-6 | Raw materials | 100% | database | 100% | database |
| | Manufacturing | 100% | database, literature and primary data | 100% | primary data |
| | Use | 100% | calculated | 100% | calculated |
| | End-of-Life | 100% | literature | 100% | literature |

The main limitations of this study are primarily related to the quality of the data used. Specifically, the study relies on unit process data from the Ecoinvent 3.9.1 database for conventional practices, while it relies more heavily on primary data provided by industrial partners for the WAAM alternative. Additionally, there is a potential bias due to considering industrial-scale processes for conventional manufacturing, compared to a medium-scale setup for WAAM. However, it is important to note that these uncertainties and potential biases have been carefully addressed through uncertainty and scenario sensitivity analysis in the study.

## 4.2. Comparison with existing knowledge

Table 39 shows some WAAM parameters from Grade2XL demonstrators in comparison to the findings from relevant existing studies [4], [5], [6]. The aspects considered are: (1) material utilization fraction, (2) energy consumption during WAAM, (3) deposition rate, (4) shielding gas flow, and (5) shielding gas composition.

**Table 39.** *Comparison of WAAM process parameters with existing literature.*

| Material utilization fraction (as material needed for 1 kg finished product) | Energy consumption (in kWh per kg) | Deposition rate (in kg/h) | Shielding gas flow (in l/min) | Shielding gas composition | Source |
|---|---|---|---|---|---|
| 0.78 | 2.72 | 1 | 12 | 98% Ar, 2% $CO_2$ | [5] |
| 0.85 | 3.07 | 1 | 12 | Ar | [6] |
| | 2.46 | 2 | | | |
| | 2.09 | 5 | | | |
| 0.41 | 1.12 | 0.1208 | 16 | 82 % Argon and 18 % $CO_2$ | [4] |
| From 0.38 to 0.96 | 1.1 - 2 | 1.9 | 15 - 20 | Different proportions of Ar, $CO_2$ and He depending on the demonstrator | Grade2XL (see supplementary information “LCI-final-Grade2XL.xlsx”) |
| | 1.5 | 6.3 | | | |

## 4.3. Health and Safety for WAAM

Health and Safety (H&S) is an important, yet complex aspect of WAAM and additive manufacturing in general. Indeed, assessing operator´s health and safety demands expertise in manufacturing processes and also involves fields such as public health and safety, quantitative metrics and environmental science [6], [7]. Additionally, various routes of exposure, including inhalation, ingestion, and skin contact with different materials, are possible, and there is a wide knowledge and concerns related to the health effects from welding [8], [9] yet there is little data on occupational diseases resulting from long-term exposure from additive manufacturing [7]. Due to the infancy of WAAM technology, there is a lack of information in scientific publications on its emissions and related health impacts. Nevertheless, WAAM operates similarly to robot-assisted electric arc welding and likely produces comparable emissions and health risks [6]. Indeed, the novelty of WAAM relates to the automation aspect of it. The major difference that WAAM, in comparison to robotic welding, could potentially have concerning human health impacts is in case of active cooling application during the printing of the parts. Thus, in the existing scientific literature about conventional welding the compounds present in welding fumes that potentially can have adverse long-term exposure effects on human health are Manganese (Mn), Hexavalent chromium (Cr VI), Nickel (Ni), Aluminum (Al) and Phosphorus (P) [6]. Similarly, in Technical Rules for Hazardous Substances (TRGS) 528 [10] three categories of hazardous substances that can be found in welding fumes are classified. The first category includes compounds harmful to the respiratory tract and lungs (e.g. iron oxides, aluminum oxide). The second lists toxic or toxic-irritating substances (e.g. fluorides, manganese oxides, zinc oxide, copper oxide). The last one identifies carcinogenic substances (e.g. chromium-(VI)-compounds, nickel oxide). For these reasons, welding fumes were included in the life cycle assessment as indoor emissions. It was possible to collect

primary data about welding fumes thanks to the help of voestalpine Böhler that provided data sheets on those measured for WAAM in RWTH Aachen lab with process parameters (e.g., shielding gas flow and type, wire rods, etc.), which are not the same ones employed for printing the demonstrators in Grade2XL. However, those were good proxies and included some of the hazardous chemicals aforementioned (i.e., Cr-IV-compounds, manganese oxides). The only issue is that ReCiPe 2016 for unspecified or indoor emissions has the same characterization factors. Furthermore, the main advantage concerning H&S considerations is the fact that WAAM is an automated process. Thus, in comparison to conventional welding we could expect minor impacts by using it, because WAAM machines are in an enclosed compartment which protects against radiation and fumes.
For what regards regulatory frameworks on H&S aspects regarding WAAM and welding fumes as for scientific publications there is a lack of rules targeting specifically this technology. However, recently there is a growing interest in adverse effect on human health of long-exposure to welding fumes both in EU [12], [13] and internationally [14]. The first one includes the technical committee of European manufacturers dedicated to welding protection and safety equipment, under the European Welding Association (EWA) [13]. The latter provides details on welding technologies' fume and gas emissions, including details on the constituents, morphology, and structure of welding fumes (e.g., particles size and chemical composition) [14]. Particularly, the health hazards associated with ultrafine particles, such as their carcinogenic and toxic irritating effects, are critically reviewed. Another aspect relevant for WAAM concerns engineering machineries and that is regulated by the *Directive 2006/42/EC* [15]. Indeed, the European Commission recognizes that the machinery sector is crucial for the economy, and reducing accidents through safe design and maintenance is essential. Ultimately, member states are responsible for ensuring safety, especially for workers and consumers using machinery. For example, Danish workers using industrial machineries related to welding technologies have to pass a mandatory safety course and the *Arbejdstilsynets executive nr.822* is the current legal foundation for the Health, Safety, and Environment (HSE) aspects [16].

# 5 Conclusions

In general, WAAM has better environmental and economic performance than conventional manufacturing. In some cases, when the applied functional grading caused improvements during the use stage of the demonstrator, this had major relevance on the total impact score of its life cycle assessment (LCA). WAAM has also potential to reduce the lead time 31% to 92% in relation to conventional options. Main contributing processes for WAAM are manufacturing process (excluding consumables and metal wires), and material input use. For conventional manufacturing option the generally the most contributing process is the material input use. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, this is due to crediting in the system modelling. Production costs are generally lower than the conventional manufacturing option, except for some demonstrators (i.e., A-1, B-5).
Below in Table 40 are reported in detail the most relevant points about the first interpretation of LCA and LCC results for each demonstrator.

**Table 40.** *Summary table with conclusion drawn from the LCA and financial LCC for each Grade2XL demonstrators. CM = conventional manufacturing; WAAM = wire-arc additive manufacturing.*

| Demonstrator | Company | Conclusion |
|---|---|---|
| A-1 **Ship propeller (small/ medium/ large)** | MAN | 1) The best scenario with medium and large ship propellers fabricated with WAAM performs slightly better than the casted alternative, due to extended lifetime and propulsive efficiency. However, the impact scores between CM and WAAM alternatives often differ by less than 5%.<br>2) The best scenario for WAAM is better than the worst from 8 to 17 impact categories out of 18 depending on the propeller size. For “Human non-carcinogenic toxicity” there are high uncertainties in the impact scores.<br>3) The most contributing life cycle process is the use stage. Excluding USE STAGE:<br>a. CM: materials have the highest contribution to the total impact score.<br>b. For WAAM: the most contributing process are the metal wires (Inconel 625 and Steel 355).<br>c. The process contribution analysis for medium and large boat propeller are the same as medium and large ship propellers LCI unit processes were increased proportionally (if Monte Carlo analysis is not used).<br>d. Important parameters in WAAM: extent of propulsive efficiency and increase of lifetime<br>4) Production costs are generally lower for the conventional manufacturing option, but the operational costs are the highest. Thus, it is important the extent of propulsive efficiency. |
| A-2b **Holding Ring (hydroelectric)** | EDF | 1) CM is worse than WAAM (best) in 12 out of 18 impact categories, while is better than WAAM (worst) in 12 out of 18 impact categories.<br>2) CM: the most contributing process is repair (including transportation and electricity use), followed by the wire production process.<br>3) In WAAM (worst) and (best) the most contributing process is the metal wire production, except for Ionizing radiation that is dominated by “WAAM energy”. As major difference between WAAM worst and best we can notice the different contribution to the overall impact from “Repair” (excluding consumables and materials), which is more relevant for WAAM worst.<br>4) Important processes in WAAM: extent of repairs.<br>5) LCC: production costs for CM are higher than WAAM |
| B-1 **Bathtub Mould (white goods)** | Villeroy & Boch | 1) CM is worse than WAAM (best) in all 18 impact categories, the latter is better than WAAM (worst) in all 18 impact categories.<br>2) Use stage is the most contributing process. Excluding it:<br>a. CM: the NDV process is the most contributing process.<br>b. WAAM: the most contributing process is the manufacturing process, except for Land use that is dominated by steel wires production. The main difference for WAAM worst and best is relative to contribution of |

| | | |
|---|---|---|
| | | the shielding gasses which is more relevant for worst scenario, particularly in the impact categories Human cancerogenic toxicity and Mineral resource scarcity.<br>3) Important processes in WAAM: energy savings during mold use<br>4) High production cost reduction (about 97%) with WAAM as less expensive material (steel) and manufacturing processes than NDV are used. |
| B-2<br>**Mould for composites (aerospace)** | GKN | 1) CM is worse than WAAM (best) in 17 out of 18 impact categories, while is better than WAAM (worst) in 6 out of 18 impact categories.<br>2) CM: the materials life cycle stage is the most contributing process except for Marine Eutrophication and Land use for which the manufacturing (including casting, milling and transportation) is the most relevant life cycle stage.<br>3) WAAM: the most contributing process is the metal wire production. The main difference between WAAM worst and best is the fact that in Ionizing radiation and Mineral resource scarcity welding fumes and WAAM energy are the most contributing processes, respectively. Additionally, in WAAM (worst) the manufacturing stage contributes generally more than in WAAM (best).<br>4) Production and life cycle costs are similar. The max production cost reduction is roughly 28%. |
| B-3b<br>**Injection Mould (optical fiber closure)** | Shapers | 1) CM is worse than WAAM (best) and (worst) in 17 out of 18 impact categories.<br>2) Use stage is the most contributing process. Excluding it:<br>c. CM: the use stage is the most contributing process except for Human cancerogenic toxicity and Mineral resource scarcity for which the materials are the most relevant process.<br>d. WAAM: the most contributing process is the manufacturing process (excluding consumables and metal wires but including the cast iron frame), except for Ionizing radiation, Marine eutrophication and Water consumption that are dominated by WAAM energy. While Land use is dominated by steel wires production and manufacturing.<br>3) Important processes: energy savings during injection mould use thanks to design for cooling channels<br>4) Lower costs achievable with WAAM. |
| B-4.1<br>**Cutting tool (automotive)** | | 1) CM is worse than WAAM (best) and (worst) in 15 out of 18 impact categories. The impact category Human non-carcinogenic toxicity presents high uncertainties for CM.<br>2) CM: the materials&manufacturing life cycle stage is the most contributing process.<br>3) WAAM: the most contributing process in manufacturing expect for Land use that is the steel wire production. The major difference between WAAM (best) and WAAM (worst) is the contribution of shielding gas to the total impact score which appears in Ionizing radiation and Water consumptions categories when WAAM (worst) is considered.<br>4) Overall cost reduction with WAAM is about 61%. |
| B-4.2<br>**Forming tool- (automotive)** | Gorenje | 5) CM is worse than WAAM (best) in 15 out of 18 impact categories. The impact category Human non-carcinogenic toxicity presents high uncertainties for CM.<br>1) CM: materials&manufacturing life cycle stage is the most contributing process.<br>6) WAAM: the most contributing process in manufacturing expect for Land use that is the steel wire production. The major difference between WAAM (best) and WAAM (worst) is the contribution of shielding gas to the total impact score which appears in Ionizing radiation and Water consumptions categories when WAAM (worst) is considered.<br>2) Overall cost reduction with WAAM is about 29%. |
| B-5<br>**Cutting tool (white goods)** | | 1) Conventional manufacturing (CM) is worse than WAAM (best) in 17 out of 18 impact categories and is also better than WAAM (worst) in 3 out of 18 impact categories.<br>2) CM: the materials life cycle stage is the most contributing process except for Global Warming, Marine Eutrophication, Fossil resource scarcity and Land use for which the manufacturing (including casting, milling and transportation) is the most relevant life cycle stage.<br>3) WAAM: the biggest difference between WAAM (best) and WAAM (worst) is the extent of contribution to the total impact score by the repair of the tool during its |

| | | |
|---|---|---|
| | | use which is much larger for the latter scenario. Except that, the most contributing processes are the metal wire production and manufacturing stage.<br>4) Overall life cycle costs are higher with WAAM (3% - 83%). |
| B-6 **Forging die (repair case)** | Kuznia Jawor | 1) CM is worse than WAAM (best) in 16 out of 18 impact categories, while is better than WAAM (worst) in 13 out of 18 impact categories<br>2) CM: the most contributing process is repair (including transportation and electricity use), followed by the wire production process.<br>3) For WAAM (worst) and (best) the most contributing process is energy consumption for manufacturing (WAAM Energy). Between the two scenarios there is not much difference as the frequency of repair of the forging die with WAAM.<br>4) Overall life cycle costs can be reduced with WAAM (78% - 97%). |

# 6 References

[1] ISO/TC 207/SC 5 Life cycle assessment, "ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework," 2006.
[2] ISO/TC 207/SC 5 Life cycle assessment, "ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines," 2006.
[3] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds., *Life Cycle Assessment: Theory and Practice*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-56475-3.
[4] T. Henckens, "Scarce mineral resources: Extraction, consumption and limits of sustainability," *Resources, Conservation and Recycling*, vol. 169, Jun. 2021, doi: 10.1016/j.resconrec.2021.105511.
[5] J. Oda, K. Akimoto, and T. Tomoda, "Long-term global availability of steel scrap," *Resources, Conservation and Recycling*, vol. 81, pp. 81–91, 2013, doi: 10.1016/j.resconrec.2013.10.002.
[6] H. P. N. Nagarajan, S. Panicker, H. Mokhtarian, E. Coatanéa, and K. R. Haapala, "Improving worker health and safety in wire arc additive manufacturing: A graph-based approach," *Procedia CIRP*, vol. 90, pp. 461–466, 2020, doi: 10.1016/j.procir.2020.01.116.
[7] V. Lunetto, A. R. Catalano, P. C. Priarone, and L. Settineri, "Comments about the human health risks related to additive manufacturing," *Smart Innovation, Systems and Technologies*, vol. 130, pp. 95–104, 2019, doi: 10.1007/978-3-030-04290-5_10.
[8] B. Sjögren, M. Albin, K. Broberg, P. Gustavsson, H. Tinnerberg, and G. Johanson, "An occupational exposure limit for welding fumes is urgently needed," *Scand J Work Environ Health*, vol. 48, no. 1, pp. 1–3, Jan. 2022, doi: 10.5271/sjweh.4002.
[9] E. Quecke, B. Quemerais, and Z. Hashisho, "Review of welding fume emission factor development," *Annals of Work Exposures and Health*, vol. 67, no. 6, pp. 675–693, Jul. 2023, doi: 10.1093/annweh/wxad024.
[10] "BAuA - Technical Rules - Technical Rules for Hazardous Substances (TRGS) - Federal Institute for Occupational Safety and Health." Accessed: Jun. 04, 2024. [Online]. Available: https://www.baua.de/EN/Service/Technical-rules/TRGS/TRGS.html
[11] "The USEtox Model | USEtox®." Accessed: Jun. 04, 2024. [Online]. Available: https://www.usetox.org/model
[12] "EU Strategic Framework on Health and Safety at Work 2021-2027 | Safety and health at work EU-OSHA." Accessed: Jun. 04, 2024. [Online]. Available: https://osha.europa.eu/en/safety-and-health-legislation/eu-strategic-framework-health-and-safety-work-2021-2027
[13] "EWA – European Welding Association." Accessed: Jun. 04, 2024. [Online]. Available: https://european-welding.org/
[14] V. E. Spiegel-Ciobanu, L. Costa, and W. Zschiesche, *Hazardous Substances in Welding and Allied Processes*. in IIW Collection. Cham: Springer International Publishing, 2020. doi: 10.1007/978-3-030-36926-2.
[15] *Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast) (Text with EEA relevance)*, vol. 157. 2006. Accessed: Jun. 04, 2024. [Online]. Available: http://data.europa.eu/eli/dir/2006/42/oj/eng
[16] "Bekendtgørelse om foranstaltninger til forebyggelse af risikoen ved arbejde med kræftfremkaldende, mutagene eller reproduktionstoksiske stoffer og materialer - Arbejdstilsynet." Accessed: Jun. 04, 2024. [Online]. Available: https://at.dk/regler/bekendtgoerelser/foranstaltninger-forebyggelse-kraeftfremkaldende-mutagene-reproduktionstoksiske-stoffer-materialer-290/