Deliverable D6.2
WP6. Lifecycle Assessment

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Delivery date 31/08/2023
Dissemination level
Version 1.0

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

Contents

Executive summary

This deliverable consists of the second iteration 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-2 (holding ring for hydroelectric power plants), B-1 (bathtub mould), B-2 (composite tool for aerospace parts), B-3 (injection mould for optical fiber closure), B-4.1 (cutting tool automotive parts), B-4.2 (forming tool automotive parts), B-5 (cutting tool for white goods) and B-6 (hot forging die repair). This second iteration LCA was based on the ILCD guidelines and the standard ISO14040/44. SimaPro 9.4.0.3 software and ecoinvent 3.8 database were used to model the life cycle assessment of the Grade2XL demonstrators.

So far, products manufactured with WAAM 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 feasible through multi-material WAAM was applied. For instance, the ship propeller showed benefits thanks to fuel savings because of reduced cavitation erosion achievable through functional grading; and Shapers´s injection mould 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 a main source of impact the feedstock production, while when WAAM was used the main source of impact were feedstock production and the consumables during manufacturing (i.e. process gas and energy consumption).

In the future, it is expected to include also uncertainty analysis for LCA, and refine the LCI for all demonstrators once they will all be fabricated through optimized WAAM.

1. LCA and LCC

The main objectives for deliverable D6.2 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, and sensitivity analysis. In particular, the sensitivity analysis included:
    - scenario sensitivity. To calculate the sensitivity coefficient the following formula was used:

      $$\%\,relative\ change\ = \frac{\Delta output}{Baseline\ scenario\ impact\ score}$$

      The scenario important was considered important, if |% relative change| ≥ 50%.
    - one-at-time (OAT) parameter perturbation. To calculate the sensitivity coefficient the following formula was used:

      $$S_{coefficient} = \frac{\frac{\Delta output}{Initial\ impact\ score}}{\frac{\Delta input}{Initial\ parameter\ value}}$$

      The parameter is considered important if $|S_{coeffient\text{-}max}|$ ≥ 50% or $|Average\text{-}S_{coefficient}|$ ≥ 30%;
- The LCA software and database used are SimaPro 9.4.0.3, and ecoinvent 3.8, respectively;
- At this stage equipment used during manufacturing were included, and it is planned to be completed for the next deliverable;
- 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).

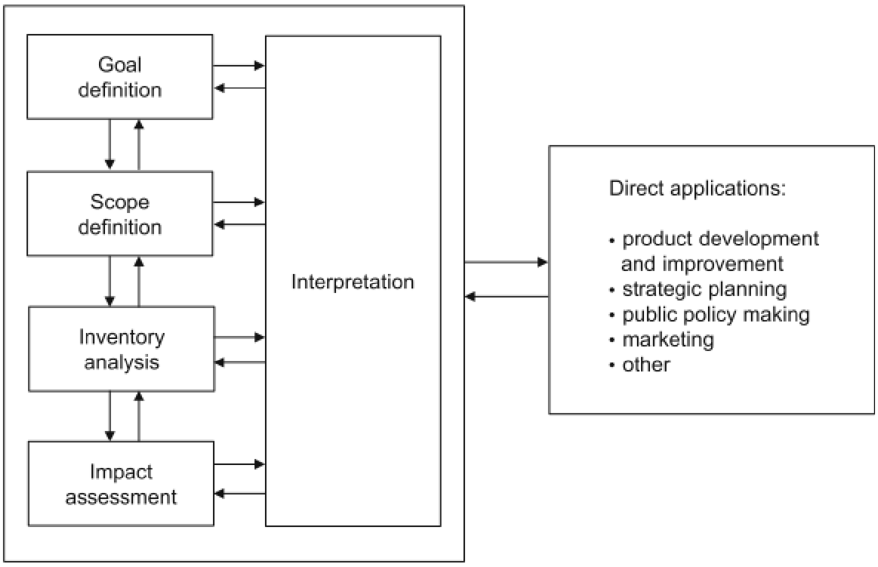


Figure 1: Conceptual framework LCA (Hauschild, Michael Z., Ralph K. Rosenbaum, and Stig Irvin Olsen 2018)

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.

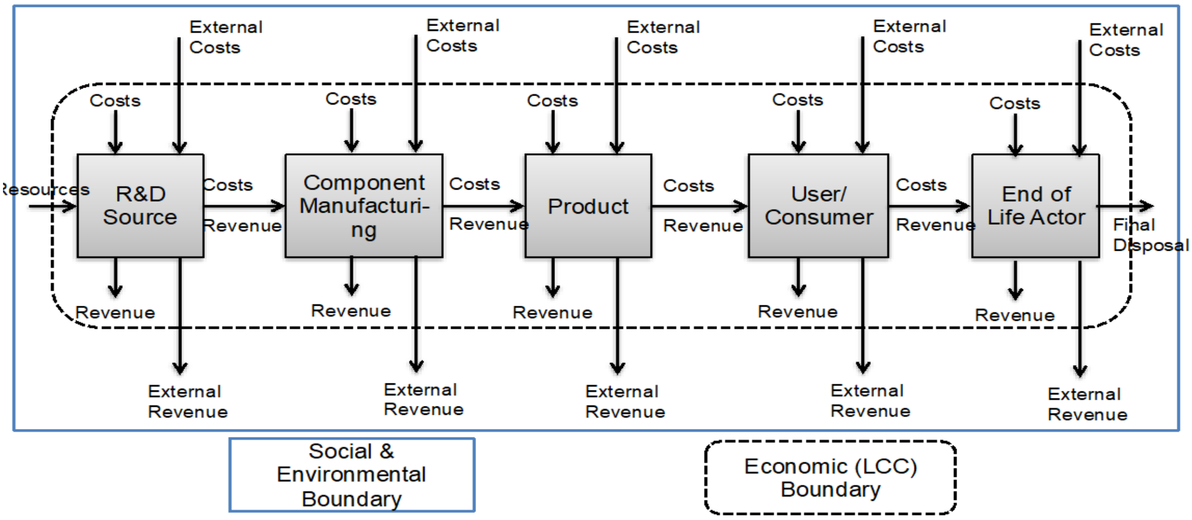


Figure 2: Conceptual framework for Life Cycle Costing (LCC). Adapted from (Rebitzer, G., and Hunkeler, D. 2003)

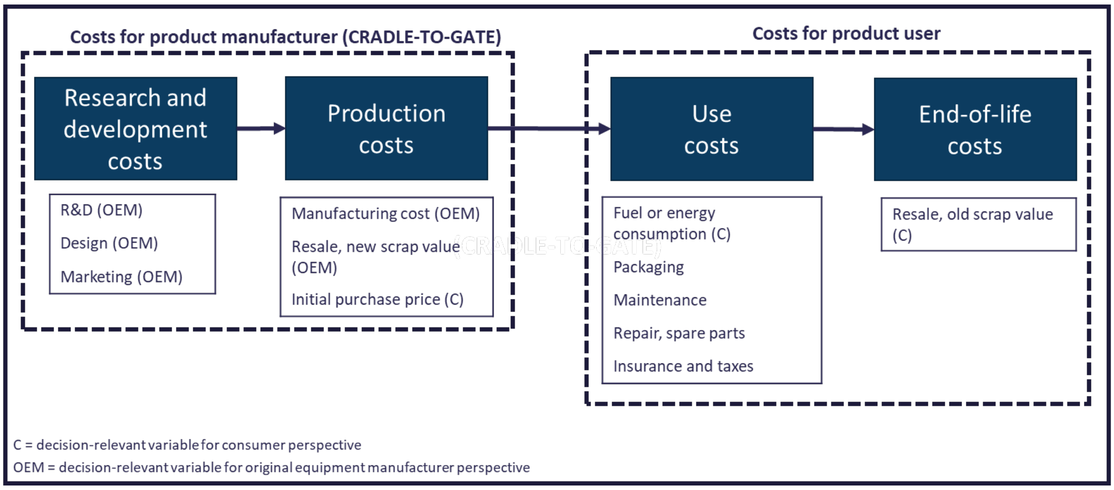


Figure 3: Life Cycle Costing for product (CRADLE-TO-GRAVE) Adapted from (Swarr 2011)

1.1. Second iteration: assessment results

This section illustrates the results of the second iteration of preliminary 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 (Hauschild, Michael Z., Ralph K. Rosenbaum, and Stig Irvin Olsen 2018). 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 (Hauschild, Michael Z., Ralph K. Rosenbaum, and Stig Irvin Olsen 2018);
- characterized results is a mandatory step of the impact assessment stage of LCA (Hauschild, Michael Z., Ralph K. Rosenbaum, and Stig Irvin Olsen 2018), 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 can be 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 sensitivity analysis;
- product life cycle cost inventories and the related graphs depicting the differences between the conventional manufacturing and the WAAM option.

Generally, the contribution to the total environmental impact of the shielding gases is relevant. This might also be connected to the fact that background data based on other technologies was considered in the preliminary assessment.

Finally, in Appendix A the assumptions and related justifications were listed for each Grade2XL demonstrator, as well as the life cycle inventory for each demonstrator.

1.1.1. Introduction

In order to develop a fair comparative LCA of alternative ways of Grade2XL demonstrators fabrication 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?" (Hauschild, Michael Z., Ralph K. Rosenbaum, and Stig Irvin Olsen 2018). Moreover, the reference flow expresses the amount of product needed to fulfill the functional unit (Hauschild, Michael Z., Ralph K. Rosenbaum, and Stig Irvin Olsen 2018), and usually this was the final weight of the finished demonstrator.
Below in Table 1 is reported 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*	1,893	903*
		Ship propeller (medium)		5,293	2,520*
		Ship propeller (large)		10,293	4,891*
A-2	EDF	Holding Ring (hydroelectric)	*Enabling the production of XX GWh** for 10 years in France*	290	489.7
B-1	Villeroy & Boch	Bathtub Mould (white goods)	*Enabling the production of 10,000 methyl methacrylate bathtubs without surface defects in the Netherlands*	1,700	1,370
B-2	GKN	Mould for composites (aerospace)	*Enabling the production of 100 aerospatial composites a year for 20 consecutive years in the UK*	181.44	181.44
				1399.68	1399.68
B-3	Shapers	Injection Mould (optical fiber closure)	*Enabling the production of 1 million thermoplastic parts of optical fiber closure for 17 consecutive years in France*	3,374	1,849
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		Cutting tool (white goods)	*Enabling the production of 100,000 pieces of back of washing machine drums for 5 consecutive years in Slovenia*	87.6	81
B-6	Kuznia Jawor	Forging die (repair case)	*Enabling the production of 2500 pieces of lifting tool for automotive parts for 2 consecutive years in Poland*	264	48

1.1.2. Demonstrators

1.1.2.1. Demonstrator A-1

This demonstrator is a ship propeller that come in three different sizes small, medium, and large. It is used from MAN ES 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. Process contribution analysis is showed only for small ship propeller (see Figure 6 and 7) as for medium and large sizes the contribution to the total impact score is the same.

Life Cycle Assessment (LCA)

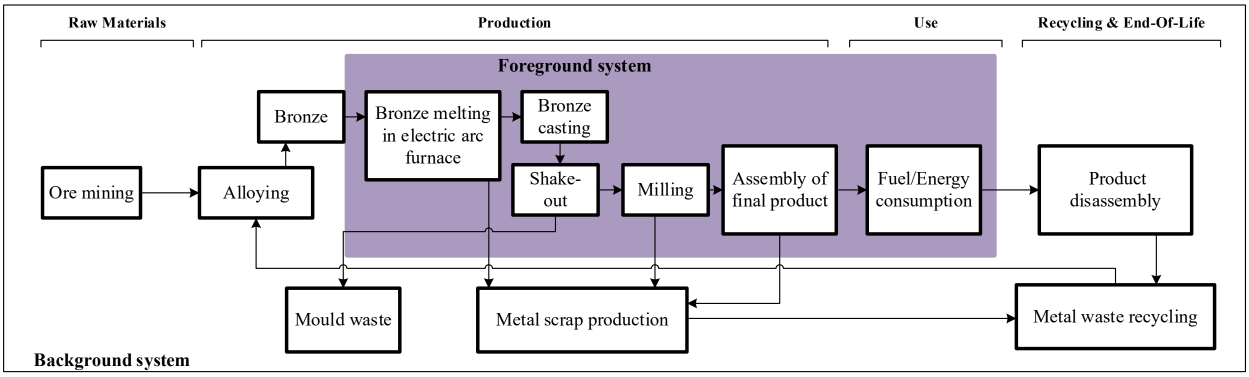


Figure 4: system boundaries of life cycle of conventional manufacturing of MAN ship propeller

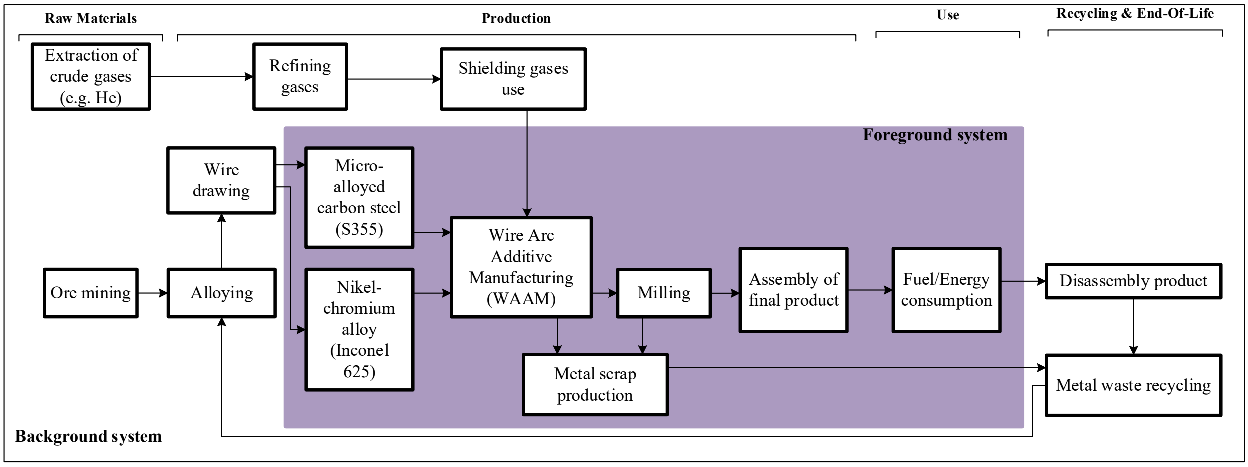


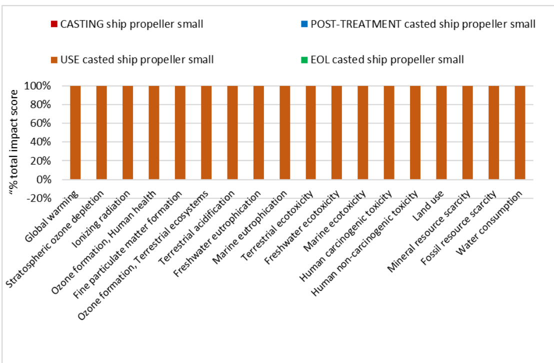
Figure 5: system boundaries of life cycle of wire arc additive manufacturing of MAN ship propeller

Table 2: characterized results of A-1 in the three different sizes calculated with ReCiPe2016 (H) midpoint life cycle impact assessment (LCIA) methodology.

Impact category	Unit	Ship propeller small		Ship propeller medium		Ship propeller large	
		CM	WAAM	CM	WAAM	CM	WAAM
Global warming	kg CO2	2.45E+12	1.06E+12	6.85E+12	2.96E+12	1.33E+13	5.74E+12
Stratospheric ozone	kg CFC11	1700838.7	734212.58	4755699.7	2048965.4	9248142.2	3976781.6
Ionizing radiation	kBq Co-	2.54E+10	1.12E+10	7.10E+10	3.13E+10	1.38E+11	6.07E+10
Ozone formation, Human health	kg NOx eq	5.09E+10	2.19E+10	1.42E+11	6.12E+10	2.77E+11	1.19E+11

Fine particulate matter formation	kg PM2.5 eq	1.62E+10	6.99E+09	4.53E+10	1.95E+10	8.81E+10	3.79E+10
Ozone formation,	kg NOx	5.12E+10	2.21E+10	1.43E+11	6.16E+10	2.79E+11	1.20E+11
Terrestrial acidification	kg SO2	5.04E+10	2.17E+10	1.41E+11	6.06E+10	2.74E+11	1.18E+11
Freshwater eutrophication	kg P eq	3.50E+08	1.54E+08	9.80E+08	4.31E+08	1.91E+09	8.36E+08
Marine eutrophication	kg N eq	8195984	3819832.7	22916716	10659999	44564852	20689704
Terrestrial ecotoxicity	kg 1,4-	6.43E+12	2.83E+12	1.80E+13	7.91E+12	3.50E+13	1.53E+13
Freshwater ecotoxicity	kg 1,4-	2.09E+10	9.87E+09	5.85E+10	2.75E+10	1.14E+11	5.34E+10
Marine ecotoxicity	kg 1,4-	3.14E+10	1.47E+10	8.79E+10	4.09E+10	1.71E+11	7.94E+10
Human carcinogenic	kg 1,4-	1.08E+11	5.10E+10	3.03E+11	1.42E+11	5.90E+11	2.76E+11
Human non-carcinogenic toxicity	kg 1,4-DCB	3.49E+11	1.60E+11	9.75E+11	4.47E+11	1.90E+12	8.68E+11
Land use	m2a crop	3.37E+10	1.48E+10	9.43E+10	4.12E+10	1.83E+11	8.00E+10
Mineral resource scarcity	kg Cu eq	4.88E+09	2.31E+09	1.37E+10	6.46E+09	2.66E+10	1.25E+10
Fossil resource scarcity	kg oil eq	7.20E+11	3.11E+11	2.01E+12	8.69E+11	3.92E+12	1.69E+12
Water consumption	m3	1.85E+09	8.60E+08	5.16E+09	2.40E+09	1.00E+10	4.66E+09

A



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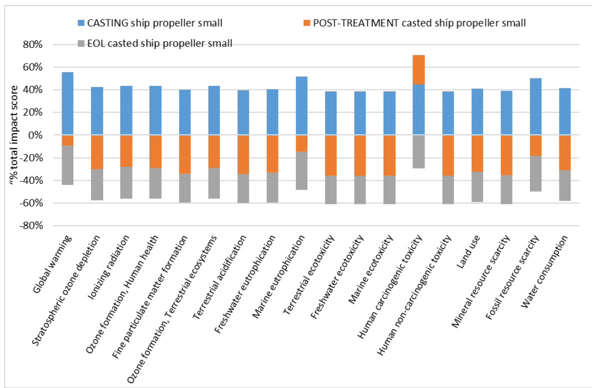

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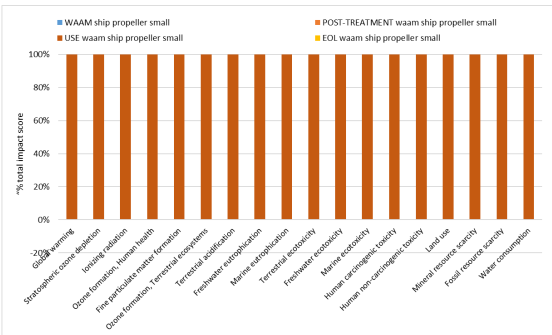

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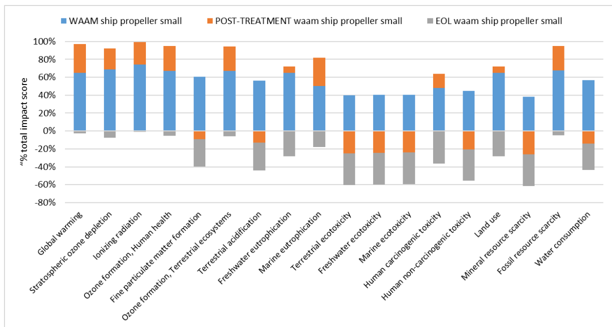


Figure 6: process contribution of small MAN ship propeller (A) produced with conventional manufacturing; (B) produced with conventional manufacturing (excluding use stage, because it is the predominant life cycle stage); (C) produced with WAAM; (D) produced with WAAM (excluding use stage, because it is the predominant life cycle stage). For both alternative when the use stage is excluded the most contributing process is the material input during manufacturing. The use stage is the main contributing category when it is considered a cradle-to-grave approach because it represents the fuel consumption for the 20 years of ship operation. For all scenarios, it is possible to notice a negative contribution of the recycled material to the total environmental impact, since this is considered a positive action in environmental terms.

Table 3: substance contribution of demonstrator A-1 for characterization ReCiPe2016 (H) for "Mineral resource scarcity" midpoint impact category

CM					WAAM				
Substance	**Compartment**	**Unit**			**Substance**	**Compartment**	**Unit**		
Iron ore, 46%Fe	Raw	kg Cu eq	2.06E+09	42%	Iron ore, 46%Fe	Raw	kg Cu eq	9.84E+08	42%
Ferronickel	Raw	kg Cu eq	1.16E+09	24%	Ferronickel	Raw	kg Cu eq	5.52E+08	24%
Ilmenite	Raw	kg Cu eq	2.86E+08	6%	Ilmenite	Raw	kg Cu eq	1.36E+08	6%
Iron ore, 63%Fe	Raw	kg Cu eq	2.08E+08	4%	Iron ore, 63%Fe	Raw	kg Cu eq	9.91E+07	4%
Rutile	Raw	kg Cu eq	1.45E+08	3%	Rutile	Raw	kg Cu eq	6.90E+07	3%
Remaining substances		kg Cu eq	1.30E+08	3%	Remaining substances		kg Cu eq	8.30E+07	4%

Table 4: summary of sensitivity analysis of MAN ship propeller. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	**Sensitivity scenarios**			**One-at-time parameter perturbation (+10%)**		
	Process	**Type of manufacturing**	**Max relative change %**	**Process**	**Type of manufacturing**	**Max $S_{coefficient}$ %**
Manufacturing stage	Recycling instead of scrap during post-treatment with milling	Both	280 (CM)/ 747 (WAAM)	Inconel amount	WAAM	825
	Change the proxy process of “bronze casting” with “brass casting”	Casting	243	Process of “bronze casting”	Casting	397
	Change the proxy process of “bronze casting” with “steel casting”	Casting	308	Shielding gases	WAAM	7784
	Single-use mould: inclusion mould materials (wood frame, sand, glue)	Casting	38	Proportion of material defects	Casting	47
Assembly scenario	Market and producers are in EU (i.e. Rotterdam and Paris) instead of in Asia	WAAM	0			
End-Of-Life				Recycled material	Both	55 (CM) / 7743 (WAAM)

Table 5: characterized results of A-1 in the three different sizes calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	**Ship propeller small**		**Ship propeller medium**		**Ship propeller large**	
	CM	**WAAM**	**CM**	**WAAM**	**CM**	**WAAM**
Human health	7.95E+00	1.67E+00	1.51E+09	6.52E+08	2.93E+09	1.27E+09
Ecosystems	2.88E-01	1.02E-01	4.69E+07	2.02E+07	9.11E+07	3.92E+07
Resources	4.15E-02	2.00E-02	3.18E+07	1.37E+07	6.18E+07	2.66E+07

Life Cycle Costing (LCC)

Table 6: 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 (€/kg)		Recycling disposed product (€/product)
		Sold scrap from product machining (€/product)
REVENUE		
Ship propeller selling (€/product)		Ship propeller selling (€/item)
		N. ship propeller (item/yr)

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 (€/kg)		Recycling disposed product (€/product)
		Sold scrap from product machining (€/product)
REVENUE		
Ship propeller selling (€/product)		Ship propeller selling (€/item)
		N. ship propeller (item/yr)

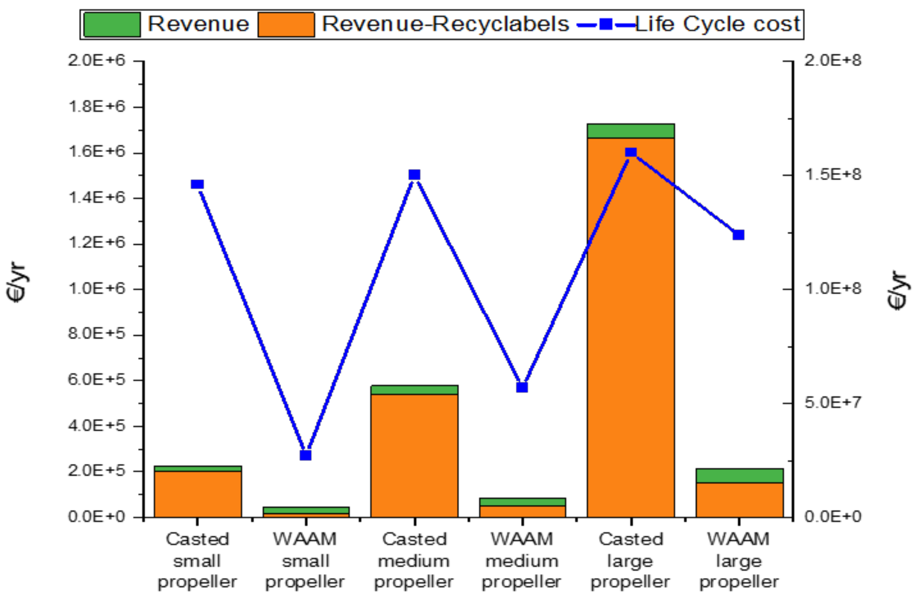


Figure 7: illustration of financial life cycle cost of the three sizes of MAN ship propellers. The y-axe on the right is for the costs and the left for the revenues.

	Casted small propeller	WAAM small propeller	Casted medium propeller	WAAM medium propeller	Casted large propeller	WAAM large propeller
Life Cycle Costs (€\year)	1.46E+08	2.71E+07	1.50E+08	5.69E+07	1.60E+08	1.24E+08
Revenue-recyclables (€\year)	2.00E+05	1.83E+04	5.42E+05	4.98E+04	1.67E+06	1.53E+05
Revenue (€\year)	2.67E+04	2.67E+04	3.56E+04	3.56E+04	6.23E+04	6.23E+04

1.1.2.2. Demonstrator A-2

This demonstrator is a holding ring for spherical turbine inlet valves in EDF hydraulic power plant (diameter 1.2 m). Wire Arc Additive Manufacturing (WAAM) will be used for its production.

Life Cycle Assessment (LCA)

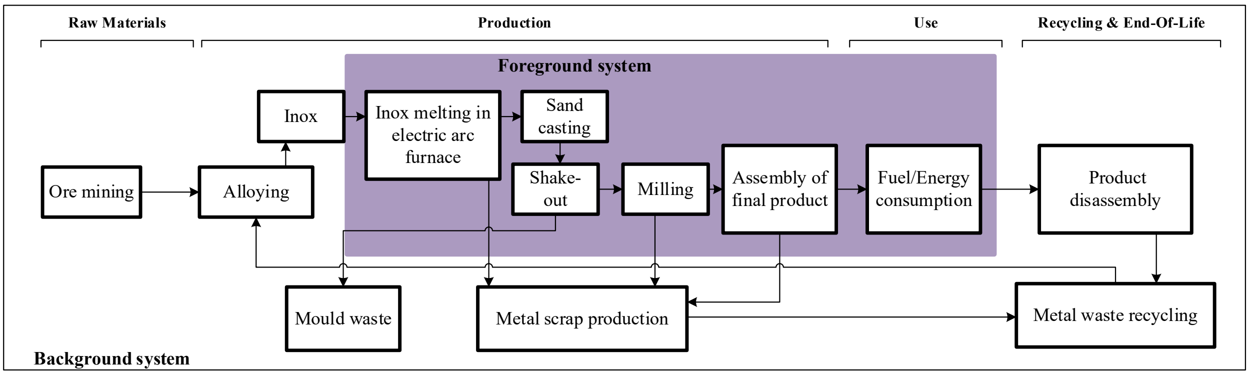


Figure 8: system boundaries of life cycle of conventional manufacturing of EDF holding ring.

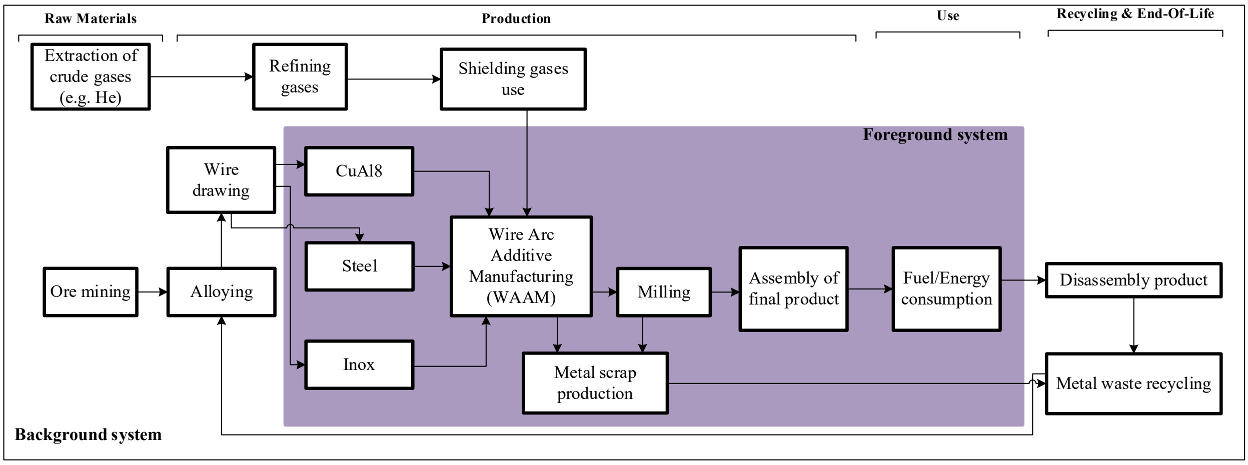


Figure 9: system boundaries of life cycle of wire arc additive manufacturing of EDF holding ring.

Table 7: characterized results A-2 ReCiPe2016 (H) midpoint. Conventional manufacturing (CM) is worse than WAAM in 13 out of 18 impact categories.

Impact category	Unit	CM	WAAM
Global warming	kg CO2 eq	5.98E+03	2.95E+03
Stratospheric ozone depletion	kg CFC11 eq	2.17E-03	1.75E-03
Ionizing radiation	kBq Co-60 eq	5.35E+02	1.32E+03
Ozone formation, Human	kg NOx eq	1.35E+01	6.38E+00
Fine particulate matter	kg PM2.5 eq	1.57E+01	5.02E+00

Ozone formation, Terrestrial	kg NOx eq	1.38E+01	6.45E+00
Terrestrial acidification	kg SO2 eq	2.21E+01	1.41E+01
Freshwater eutrophication	kg P eq	6.55E+00	3.57E+00
Marine eutrophication	kg N eq	7.87E-01	3.27E-01
Terrestrial ecotoxicity	kg 1,4-DCB	1.12E+05	3.90E+05
Freshwater ecotoxicity	kg 1,4-DCB	3.82E+03	1.85E+04
Marine ecotoxicity	kg 1,4-DCB	4.67E+03	2.22E+04
Human carcinogenic toxicity	kg 1,4-DCB	4.78E+03	5.49E+02
Human non-carcinogenic	kg 1,4-DCB	1.26E+04	8.96E+03
Land use	m2a crop eq	3.67E+02	4.71E+02
Mineral resource scarcity	kg Cu eq	3.87E+02	-1.39E+01
Fossil resource scarcity	kg oil eq	1.56E+03	8.71E+02
Water consumption	m3	8.77E+01	8.26E+01

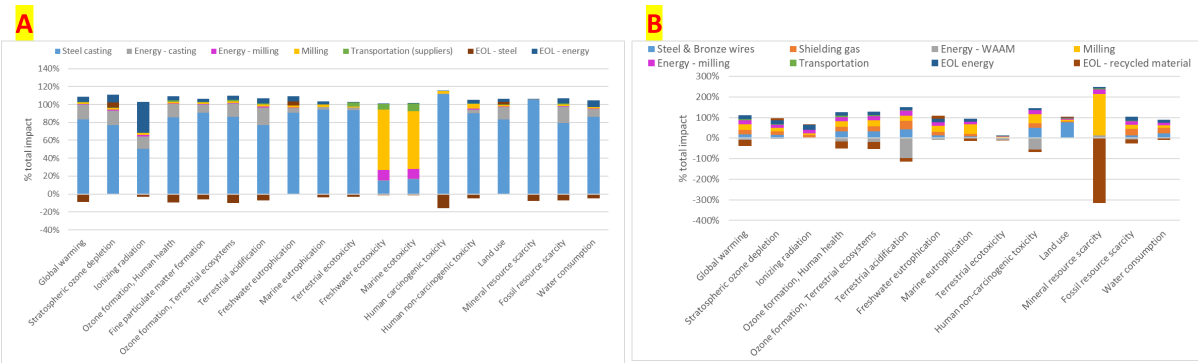


Figure 10: process contribution of EDF holding ring produced with (A) conventional manufacturing; (B) WAAM. By looking at (A) the steel casting process is the most contributing process except that for Ionizing radiation for which the energy for recycling is the most relevant process. For (B) the most contributing processes are the shielding gas used and the steel&bronze wire rods production. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, since this is considered a positive action in environmental terms.

Table 8: summary of sensitivity analysis of EDF holding ring. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficienct}$ %
Manufacturing stage	Stainless steel converted to low-alloyed steel	WAAM	4419	Weight holding ring	Both	100
				Shielding gas	WAAM	16

Table 9: Characterized results of A-2 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	2.93E+09	1.27E+09
Ecosystems	9.11E+07	3.92E+07
Resources	6.18E+07	2.66E+07

Life Cycle Costing (LCC)

Table 10: inventory of costs/revenues throughout the whole life cycle of demonstrator A-2

CM	
COSTS	
Manufacturing	
Total cost per holding ring (€)	Cost steel block (€)
	Mould for casting (€)
REVENUE-RECYCLABLES	
Recycling - Scrapping value (€/kg)	Recycling disposed product (€/product)
	Sold scrap from product machining (€/product)
REVENUE	
Total revenue from electricity selling (€/yr)	Electricity price (€/kWh)
	Electricity produced (GWh/yr)

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 (€/kg)	Recycling - Scrapping value (€/kg)	
	Sold scrap from product machining (€/product)	
REVENUE		
Total revenue from electricity selling (€/yr)	Electricity price (€/kWh)	
	Electricity produced (GWh/yr)	

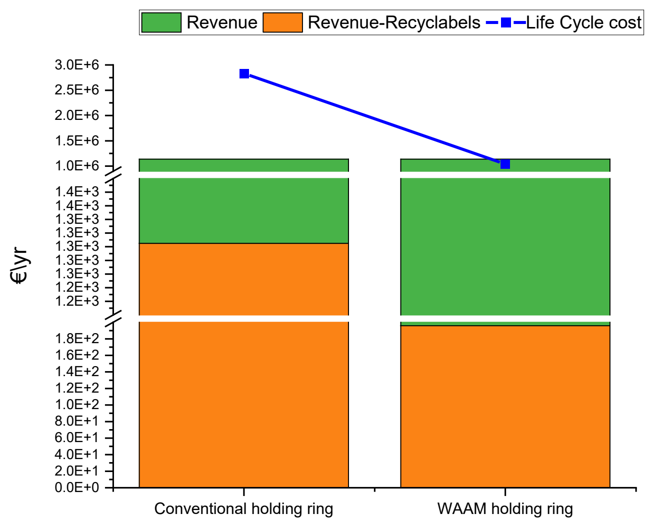


Figure 11: illustration of financial life cycle cost of EDF holding ring.

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)	Revenue (€\year)
Conventional holding ring	2.83E+06	1.31E+03	1.14E+06
WAAM holding ring	1.04E+06	1.96E+02	1.14E+06

1.1.2.3. 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. Wire Arc Additive Manufacturing (WAAM) will be used for its production.

Life Cycle Assessment (LCA)

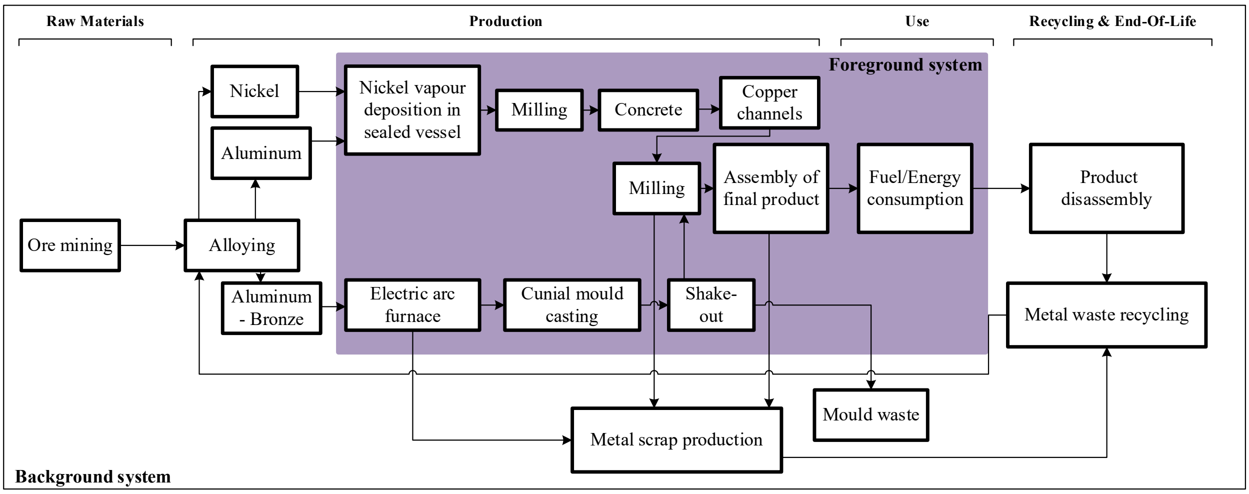


Figure 12: system boundaries of life cycle of conventional manufacturing of Villeroy&Boch bathtub mould.

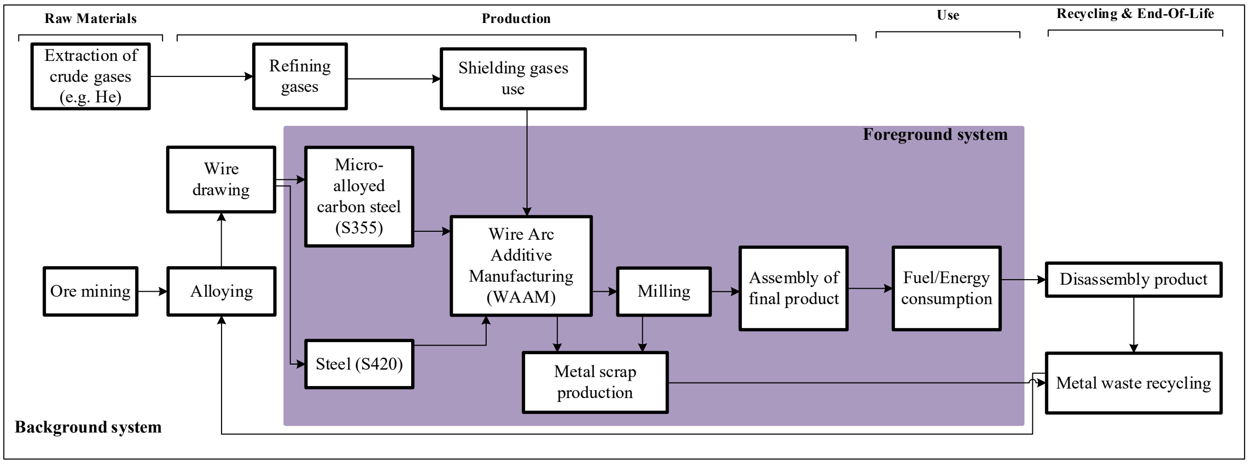


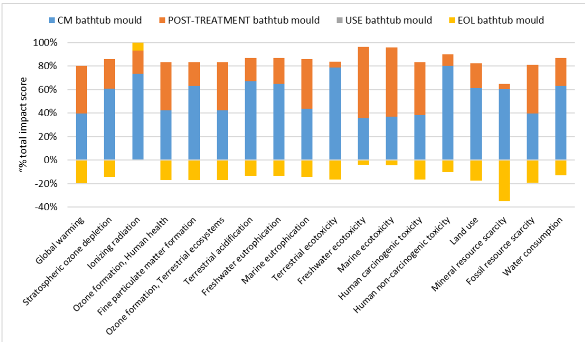
Figure 13: system boundaries of life cycle of wire arc additive manufacturing of Villeroy&Boch bathtub mould

Table 11: characterized results B-1 ReCiPe2016 (H) midpoint. CM is worse than WAAM in all impact categories, except

Impact category	Unit	CM	WAAM
Global warming	kg CO2 eq	3.38E+04	2.46E+03
Stratospheric ozone depletion	kg CFC11 eq	1.96E-02	2.63E-03
Ionizing radiation	kBq Co-60 eq	3.38E+03	5.01E+03
Ozone formation, Human	kg NOx eq	1.23E+02	2.94E+00
Fine particulate matter	kg PM2.5 eq	1.24E+02	9.42E-02
Ozone formation, Terrestrial	kg NOx eq	1.25E+02	2.75E+00
Terrestrial acidification	kg SO2 eq	3.48E+02	5.51E+00
Freshwater eutrophication	kg P eq	3.69E+01	2.27E+00
Marine eutrophication	kg N eq	2.07E+00	2.29E-01
Terrestrial ecotoxicity	kg 1,4-DCB	1.60E+06	1.19E+06
Freshwater ecotoxicity	kg 1,4-DCB	4.79E+04	7.36E+01

Marine ecotoxicity	kg 1,4-DCB	5.87E+04	7.01E+02
Human carcinogenic toxicity	kg 1,4-DCB	5.31E+03	-7.08E+02
Human non-carcinogenic	kg 1,4-DCB	2.88E+05	3.34E+03
Land use	m2a crop eq	1.80E+03	4.82E+02
Mineral resource scarcity	kg Cu eq	1.32E+03	-1.35E+02
Fossil resource scarcity	kg oil eq	8.41E+03	1.01E+03
Water consumption	m3	4.30E+02	9.26E+01

A



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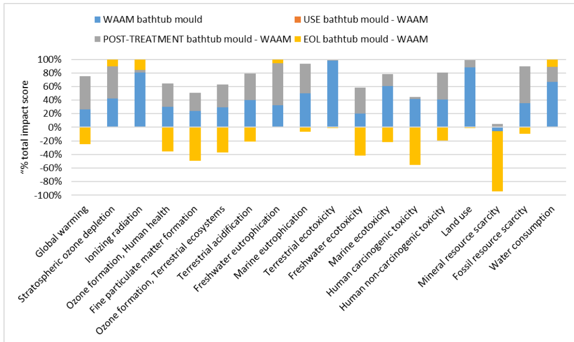


Figure 14: process contribution of Villeroy & Boch bathtub mould produced with (A) conventional manufacturing, and (B) wire arc additive manufacturing. By looking at (A) and (B)it is *possible to see that the most contributing processes for this scenario is: the manufacturing stage.* For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, since this is considered a positive action in environmental terms.

Table 12: summary of sensitivity analysis of Villeroy&Boch bathtub mould. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage	Shielding gas flow rate → From 0.68 kg / kg product to 0.336 kg / kg product	WAAM	668	Weight bathtub mould	Both	100

Table 13: characterized results of B-1 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	8.06E+00	-5.92E-03
Ecosystems	1.93E-01	1.77E-02
Resources	9.57E-02	6.44E-03

Life Cycle Costing (LCC)

Table 14: 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 (€/kg)	Recycling - Scrapping value (€/kg)	
	Sold scrap from product machining (€/product)	
REVENUE		
Bathtub produced by mould (€)	Bathtub price (€)	
	N. bathtub produced (item/yr)	
	Bathtub produced with mould (€)	

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 (€/kg)	Recycling - Scrapping value (€/kg)	
	Sold scrap from product machining (€/product)	
REVENUE		
Bathtub produced by mould (€)	Bathtub price (€)	
	N. bathtub produced (item/yr)	
	Bathtub produced with mould (€)	

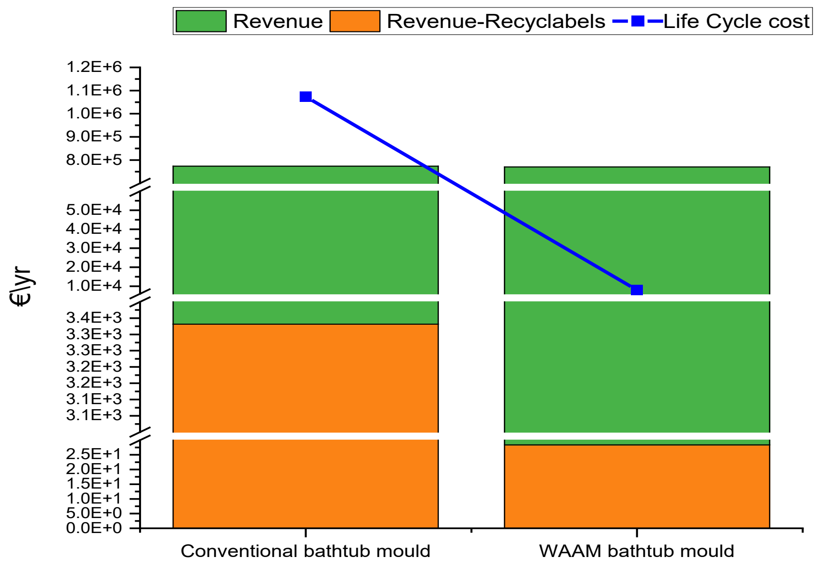


Figure 15: illustration of financial life cycle cost of Villeroy&Boch bathtub mould. The y-axe on the right is for the costs and the left for the revenues.

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)	Revenue (€\year)
Conventional bathtub mould	1.07E+06	3.33E+03	7.70E+05
WAAM bathtub mould	8.02E+03	2.84E+01	7.70E+05

1.1.2.4. Demonstrator B-2

This demonstrator is a composite tool for production of composited aerospace parts by GKN. Wire Arc Additive Manufacturing (WAAM) will be used for its production.

Life Cycle Assessment (LCA)

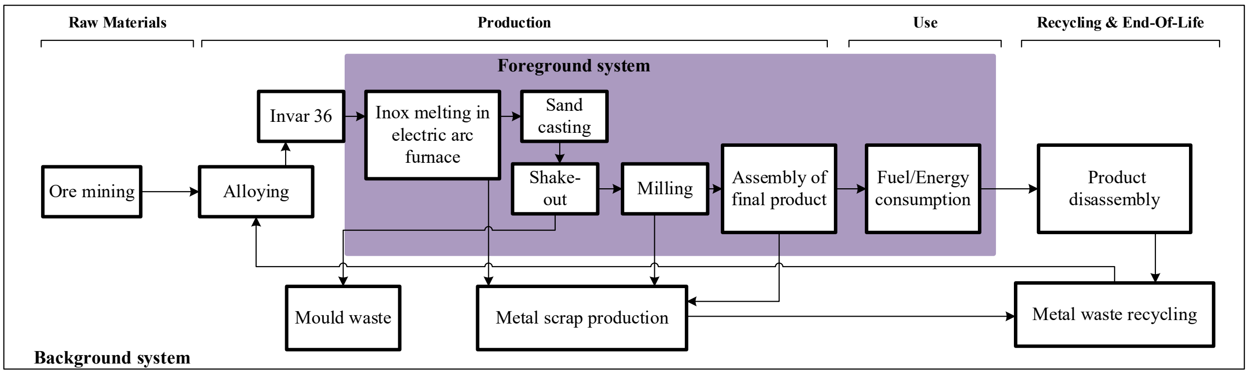


Figure 16: system boundaries of life cycle of conventional manufacturing of GKN composite tool.

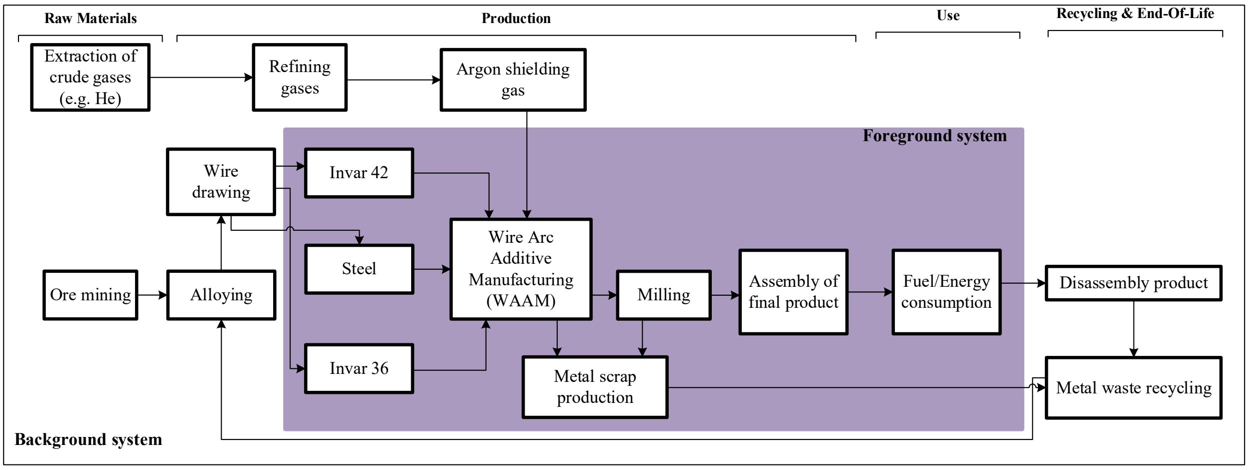


Figure 17: system boundaries of life cycle of wire arc additive manufacturing (WAAM) of GKN composite tool.

Table 15: characterized results B-2 ReCiPe2016. The composite tool produced with conventional manufacturing in both sizes (i.e. small, large) is worse in all impact categories.

Impact category	Unit	Small		Large	
		CM	WAAM	CM	WAAM
Global warming	kg CO2 eq	4.35E+03	1.57E+03	3.07E+04	1.19E+04
Stratospheric ozone depletion	kg CFC11 eq	2.41E-03	9.24E-04	1.74E-02	7.03E-03
Ionizing radiation	kBq Co-60 eq	5.76E+02	4.96E+02	3.97E+03	3.79E+03
Ozone formation, Human health	kg NOx eq	1.34E+01	4.20E+00	9.76E+01	3.19E+01
Fine particulate matter formation	kg PM2.5 eq	4.96E+01	1.34E+01	3.77E+02	1.03E+02
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.38E+01	4.29E+00	1.00E+02	3.26E+01
Terrestrial acidification	kg SO2 eq	1.52E+02	4.11E+01	1.16E+03	3.17E+02
Freshwater eutrophication	kg P eq	3.90E+00	1.50E+00	2.85E+01	1.14E+01
Marine eutrophication	kg N eq	4.60E-01	1.38E-01	3.43E+00	1.05E+00
Terrestrial ecotoxicity	kg 1,4-DCB	2.41E+05	6.23E+04	1.85E+06	4.80E+05
Freshwater ecotoxicity	kg 1,4-DCB	1.13E+03	4.31E+02	8.51E+03	3.31E+03
Marine ecotoxicity	kg 1,4-DCB	1.53E+03	5.65E+02	1.16E+04	4.34E+03
Human carcinogenic toxicity	kg 1,4-DCB	2.57E+03	6.24E+02	1.97E+04	4.80E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.05E+04	5.91E+03	1.55E+05	4.54E+04

Land use	m2a crop eq	1.53E+02	5.57E+01	1.12E+03	4.25E+02
Mineral resource scarcity	kg Cu eq	5.53E+02	1.40E+02	4.26E+03	1.08E+03
Fossil resource scarcity	kg oil eq	1.09E+03	4.25E+02	7.71E+03	3.22E+03
Water consumption	m3	1.94E+02	6.59E+01	1.47E+03	5.06E+02

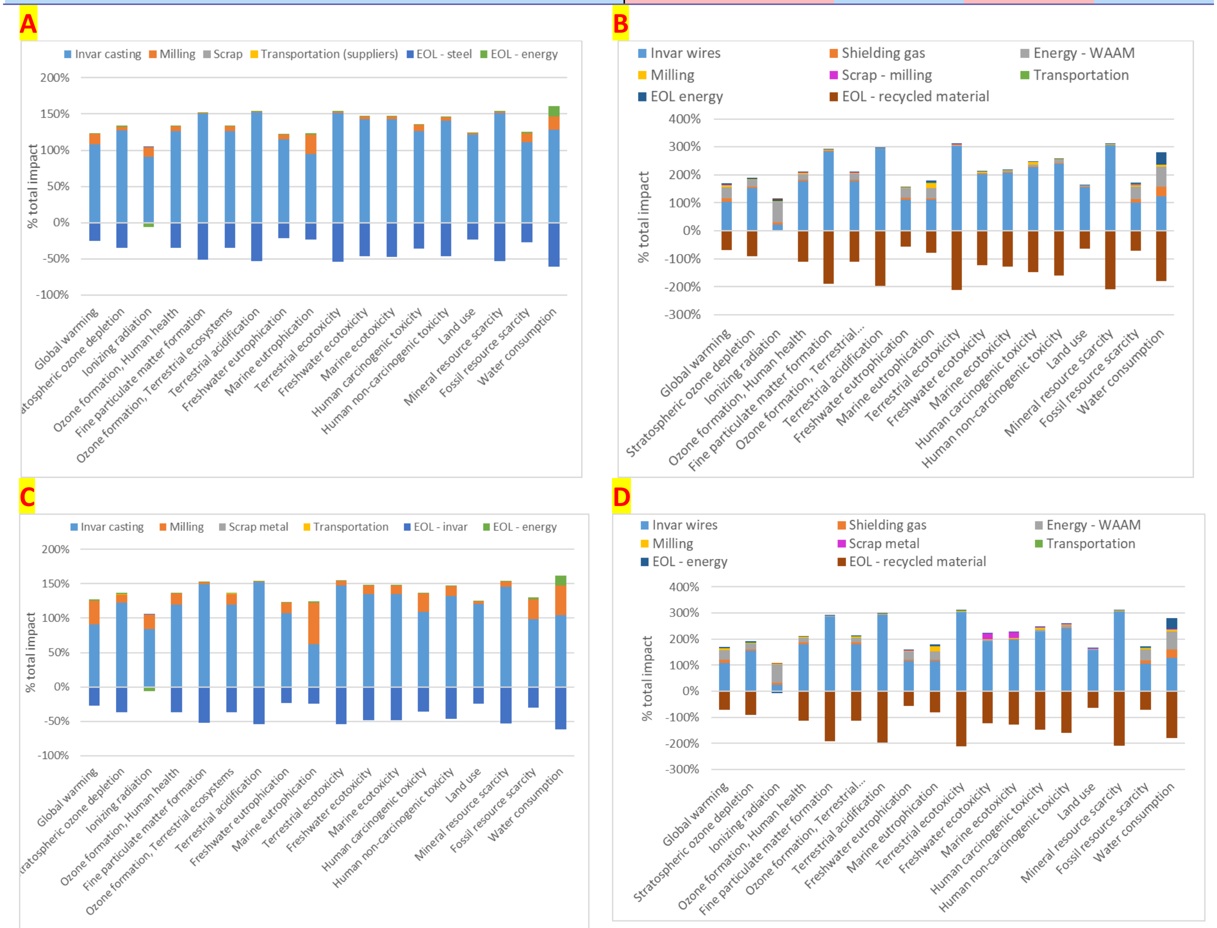


Figure 18: process contribution of GKN Fokker composite tool produced with (A) conventional manufacturing (small); (B) wire arc additive manufacturing (small); (C) conventional manufacturing (large); (D) wire arc additive manufacturing (large). By looking at (A)/(C) the most contributing process generally is Invar casting (that includes the material input itself) and energy consumption during EoL for Ionizing radiation category. For (B)/(D) the most contributing process overall is the Invar wire rods production. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, since this is considered a positive action in environmental terms.

Table 16: summary of sensitivity analysis of GKN composite tool. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage	Shielding gas flow rate → From 0.59 kg / kg product to 1.68 kg / kg product	WAAM	9	Weight composite tool	Both	100 (CM) / (AM)
	Scrap rate → from 19% to 22%	WAAM	10			

Table 17: characterized results of B-2 in the two different sizes calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	Small		Large	
	CM	WAAM	CM	WAAM
Human health	2.03E+00	5.60E-01	1.54E+01	4.29E+00
Ecosystems	3.79E-02	1.15E-02	2.84E-01	8.77E-02
Resources	1.40E-02	4.57E-03	1.03E-01	3.48E-02

Life Cycle Costing (LCC)

Table 18: inventory of costs/revenues throughout the whole life cycle of demonstrator B-2

CM		
COSTS		
Manufacturing		
Total cost per tool (€)	Cost casted composite tool (€)	
	Machining - total (€)	Machining - Manual labour (€/h)
		Machining (h)
REVENUE-RECYCLABLES		
Recycling - Scrapping value (€/kg)	Recycling - Scrapping value (€/kg)	
	Sold scrap from product machining (€/product)	
REVENUE		
Composite produced by tool (€)	Aerospatial composite price (€)	
	N. aerospatial composite produced (item/yr)	
	Aerospatial composite produced with tool (item)	

WAAM		
COSTS		
Manufacturing		
Total cost per composite 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 (€/kg)	Recycling - Scrapping value (€/kg)	
	Sold scrap from product machining (€/product)	
REVENUE		
Composite produced by tool (€)	Aerospatial composite price (€)	
	N. aerospatial composite produced (item/yr)	
	Aerospatial composite produced with tool (item)	

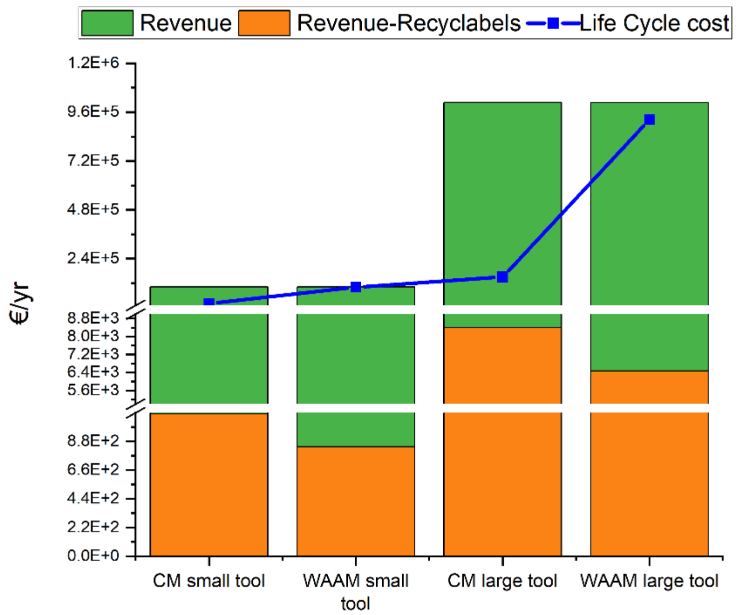


Figure 19: illustration of financial life cycle cost of GKN composite tool small and large.

	Casted small tool	WAAM small tool	Casted large tool	WAAM large tool
Life Cycle Costs (€\year)	2.00E+04	1.00E+05	1.50E+05	9.23E+05
Revenue-recyclables (€\year)	1.09E+03	8.39E+02	8.40E+03	6.47E+03
Revenue (€\year)	1.00E+05	1.00E+05	1.00E+06	1.00E+06

1.1.2.5. Demonstrator B-3

This demonstrator is an injection mould for plastic optical fiber closure used by Shapers. The mould is composed of fixed and mobile half. Wire Arc Additive Manufacturing (WAAM) will be used for its fixed and moving halves production.

Life Cycle Assessment (LCA)

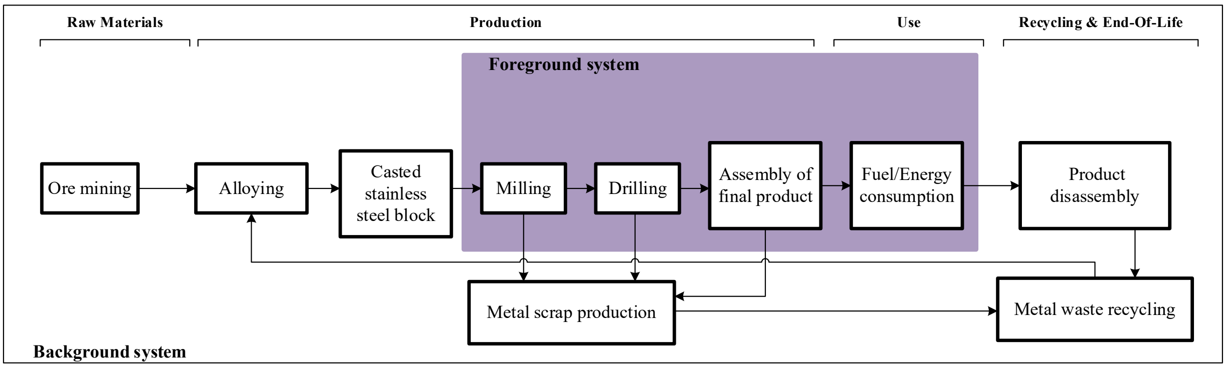


Figure 20: system boundaries of life cycle of conventional manufacturing of Shapers mould.

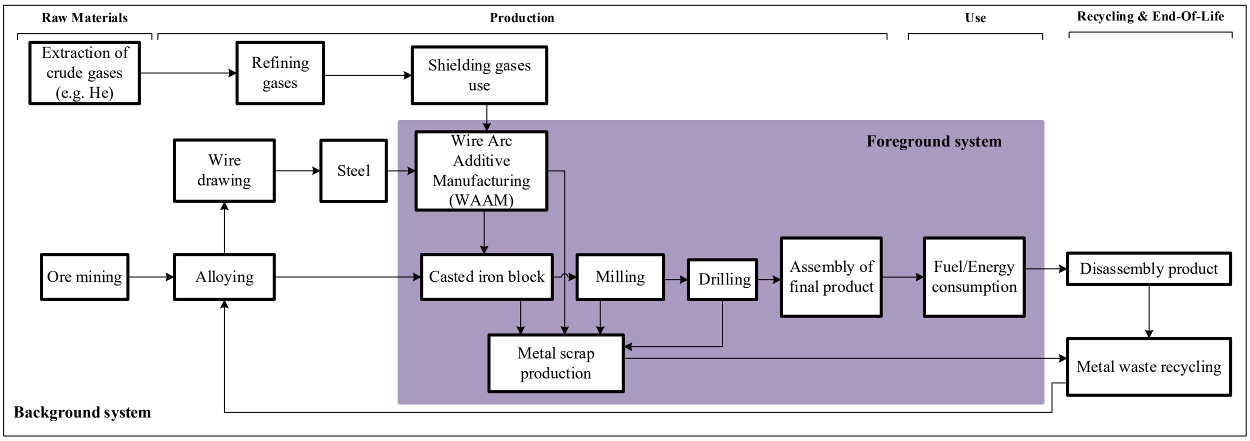


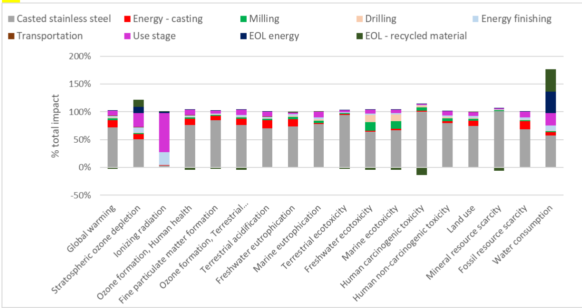
Figure 21: system boundaries of life cycle of wire arc additive manufacturing of Shapers mould.

Table 19: characterized results B-3 ReCiPe2016 (H) midpoint. CM is worse than WAAM in all impact categories.

Impact category	Unit	CM	WAAM
Global warming	kg CO2 eq	9.28E+04	9.22E+03
Stratospheric ozone depletion	kg CFC11 eq	4.36E-02	9.55E-03
Ionizing radiation	kBq Co-60 eq	8.97E+04	4.68E+04
Ozone formation, Human	kg NOx eq	2.09E+02	2.11E+01
Fine particulate matter	kg PM2.5 eq	2.28E+02	1.31E+01
Ozone formation, Terrestrial	kg NOx eq	2.14E+02	2.14E+01
Terrestrial acidification	kg SO2 eq	3.32E+02	3.31E+01

Freshwater eutrophication	kg P eq	9.47E+01	4.66E+00
Marine eutrophication	kg N eq	1.29E+01	1.12E+00
Terrestrial ecotoxicity	kg 1,4-DCB	1.51E+06	3.95E+04
Freshwater ecotoxicity	kg 1,4-DCB	1.11E+04	6.35E+02
Marine ecotoxicity	kg 1,4-DCB	1.49E+04	8.18E+02
Human carcinogenic toxicity	kg 1,4-DCB	6.79E+04	3.63E+03
Human non-carcinogenic	kg 1,4-DCB	1.88E+05	1.36E+04
Land use	m2a crop eq	5.48E+03	3.83E+02
Mineral resource scarcity	kg Cu eq	5.48E+03	8.88E+00
Fossil resource scarcity	kg oil eq	2.44E+04	2.74E+03
Water consumption	m3	1.71E+03	3.38E+02

A



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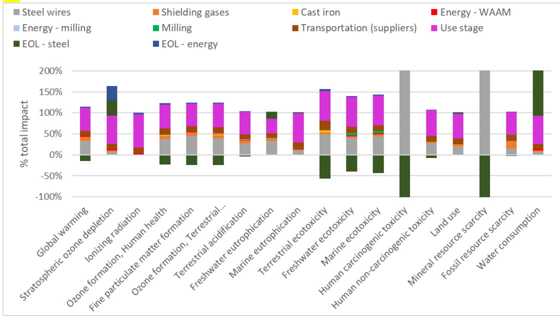

Figure 22: process contribution of Shapers injection mould produced with (A) conventional manufacturing; (B) WAAM. For (A) the most contributing process is the production of the casted stainless steel, except for Ionizing radiation for which the use stage (which is the energy consumption to produce automotive parts for 17 consecutive years) is the major contributor. By looking at (B) the most contributing process is the use stage, but there are few exceptions. EOL is the most contributing process for water consumption, and steel wires for Human carcinogenic and Mineral resource scarcity. For all scenarios it is possible to notice a negative contribution of the recycled material to the total environmental impact, since this is considered a positive action in environmental terms.

Table 20: summary of sensitivity analysis of ARKK injection mould. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage	*Steel, low-alloyed {GLO}| market for | APOS, U*	CM	94	Shielding gas	WAAM	3
				Milling	CM	7
Use stage				Energy for use stage	WAAM	74
				Energy for use stage	CM	72

Table 21: Characterized results of B-3 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	2.09E+01	1.35E+00
Ecosystems	3.46E-01	2.99E-02
Resources	2.84E-01	2.70E-02

Life Cycle Costing (LCC)

Table 22: inventory of costs/revenues throughout the whole life cycle of demonstrator B-3

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 (€/kg)		Recycling disposed product (€/product)
		Sold scrap from product machining (€/product)
REVENUE		
Composite produced by tool (€)		Optical fiber closure price (€)
		N. optical fiber closure produced (item/yr)
		Optical fiber closure produced with tool (item)

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 (€/kg)		Recycled disposed product (€/product)
		Sold scrap from product machining (€/product)
REVENUE		
Composite produced by tool (€)		Optical fiber closure price (€)
		N. optical fiber closure produced (item/yr)
		Optical fiber closure produced with tool (item)

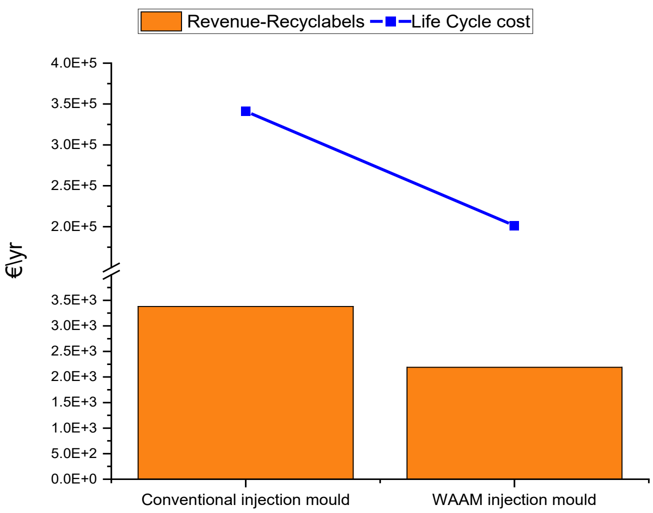

Figure 23: illustration of financial life cycle cost of Shapers injection mould.

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)
Conventional injection mould	3.54E+05	3.38E+03
WAAM injection mould	2.44E+05	2.19E+03

1.1.2.6. 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 for the production of it, instead of conventional manufacturing.

Life Cycle Assessment (LCA)

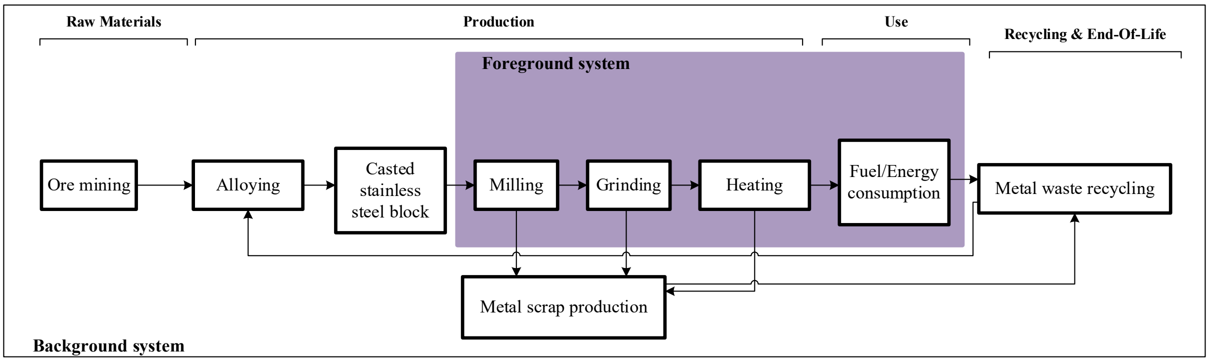

Figure 24: system boundaries of life cycle of conventional manufacturing Gorenje Orodjarna cutting tool.

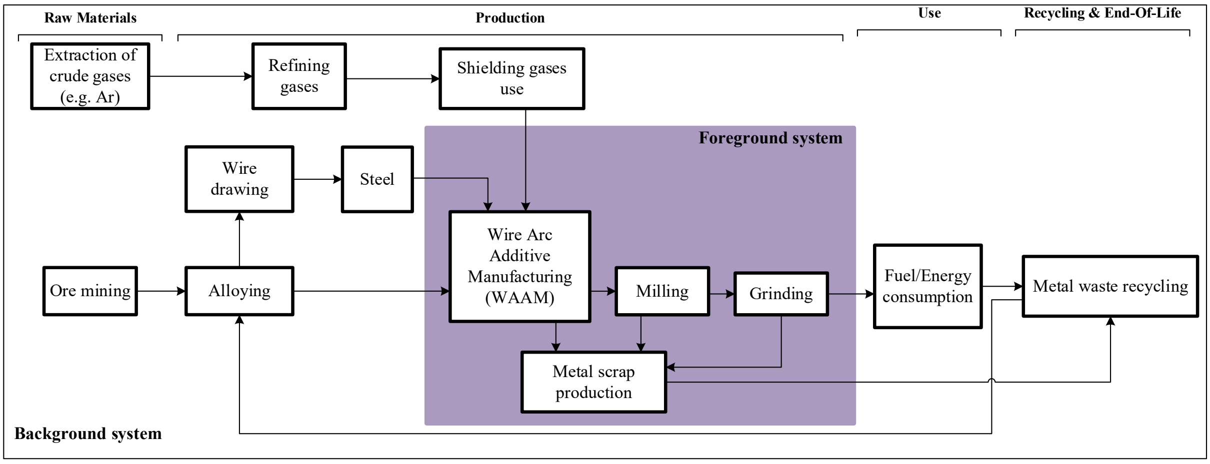

Figure 25: system boundaries of life cycle of wire arc additive manufacturing Gorenje Orodjarna cutting tool.

Table 23: characterized results for B-4.1 using ReCiPe2016 (H) midpoint. For each midpoint impact category in light red is highlighted the alternative with the worse impact score. WAAM is worse than CM for all impact categories.

Impact category	Unit	CM	WAAM
Global warming	kg CO_2 eq	1.31E+02	1.81E+02
Stratospheric ozone depletion	kg CFC11 eq	5.51E-05	7.91E-05
Ionizing radiation	kBq Co-60 eq	3.33E+01	4.84E+01
Ozone formation, Human health	kg NO_x eq	2.83E-01	3.97E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.53E-01	4.83E-01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.88E-01	4.03E-01
Terrestrial acidification	kg SO_2 eq	4.98E-01	6.93E-01
Freshwater eutrophication	kg P eq	1.13E-01	1.49E-01
Marine eutrophication	kg N eq	9.48E-03	1.10E-02
Terrestrial ecotoxicity	kg 1,4-DCB	2.43E+03	3.35E+03
Freshwater ecotoxicity	kg 1,4-DCB	2.20E+01	2.68E+01
Marine ecotoxicity	kg 1,4-DCB	2.85E+01	3.48E+01
Human carcinogenic toxicity	kg 1,4-DCB	1.20E+02	1.56E+02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.15E+02	2.78E+02

Land use	m2a crop eq	4.66E+00	6.42E+00
Mineral resource scarcity	kg Cu eq	6.69E+00	8.76E+00
Fossil resource scarcity	kg oil eq	3.21E+01	4.74E+01
Water consumption	m^3	1.85E+00	2.98E+00

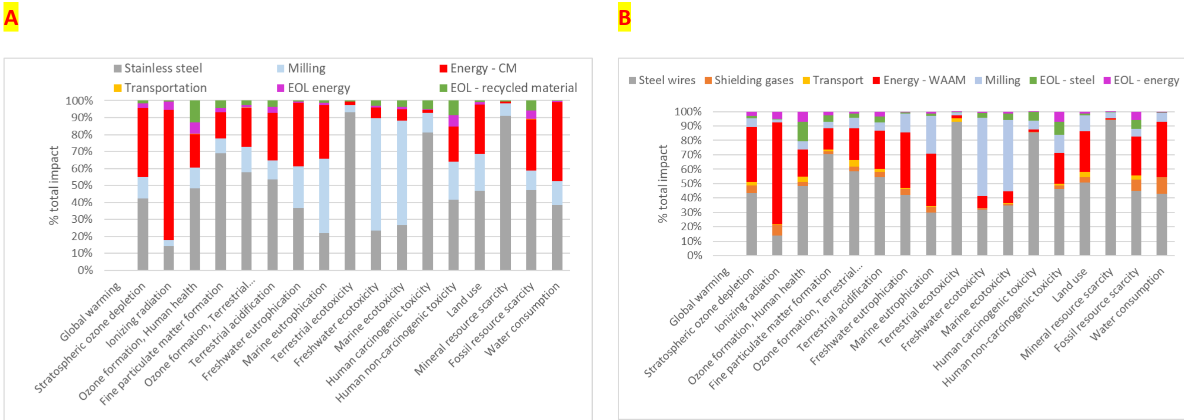

Figure 26: Process contribution of Gorenje Orodjarna cutting tool demonstrator B4.1 produced with (A) casting; (B) WAAM. For (A) the most contributing processes are the production of the casted stainless steel and milling, except for Ionizing radiation for which the energy for recycling and conventional manufacturing are the major contributors. By looking at (B) the most contributing process is the steel wire rods production, but there are few exceptions. Scrap metal produced during manufacturing of the demonstrator is the most contributing process for freshwater ecotoxicity, and energy consumption for EoL for production for Ionizing radiation. For all scenarios, it is possible to notice a negative contribution of the recycled material to the total environmental impact, since this is considered a positive action in environmental terms.

Table 24: summary of sensitivity analysis of Gorenje Orodjarna cutting tool demonstrator B4.1. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage	Shielding gas flow rate → From 0.56 kg / kg product to 1.68 kg / kg product	WAAM	5	Weight composite tool	Both	100 (CM) / (AM)
	Scrap rate → from 19% to 22%	WAAM	10	Electricity	CM	7

Table 25: Characterized results of B-4.1 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	3.31E-02	4.49E-02
Ecosystems	4.63E-04	6.27E-04
Resources	2.93E-04	4.24E-04

Life Cycle Costing (LCC)

Table 26: inventory of costs/revenues throughout the whole life cycle of demonstrator B4.1

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 (€/kg)		Recycling disposed product (€/product)
		Sold scrap from product machining (€/product)
REVENUE		
Automotive parts selling (€/ yr)		Automotive part price (€/ product)
		N. automotive part produced (n. parts/ product)

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 (€/kg)	Recycling disposed product (€/product)	
	Sold scrap from product machining (€/product)	
REVENUE		
Automotive parts selling (€/ yr)	Automotive part price (€/ product)	
	N. automotive part produced (n. parts/ product)	

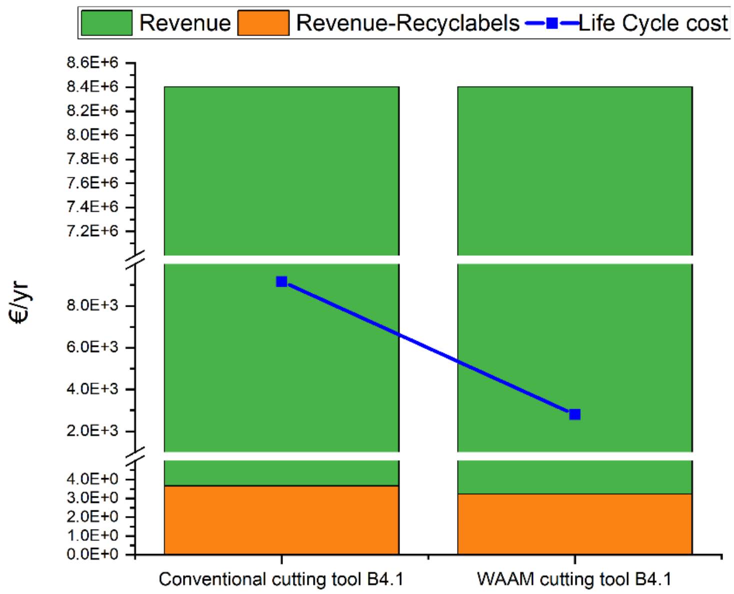

Figure 27: illustration of financial life cycle cost of Gorenje Orodjarna cutting tool demonstrator B4.1.

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)	Revenues (€\year)
Conventional cutting tool (automotive)	9.17E+03	3.66E+00	8.40E+06
WAAM cutting tool (automotive)	2.80E+03	3.23E+00	8.40E+06

1.1.2.7. 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.

Life Cycle Assessment (LCA)

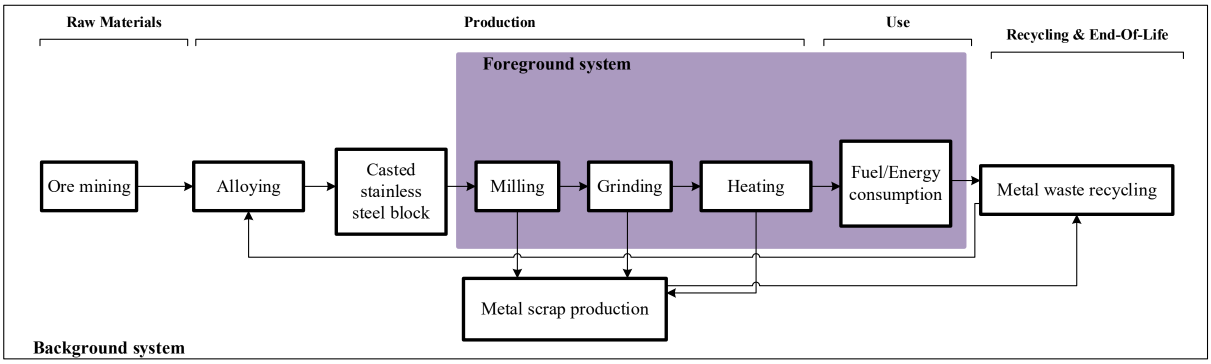

Figure 28: system boundaries of life cycle of conventional manufacturing Gorenje Orodjarna forming tool.

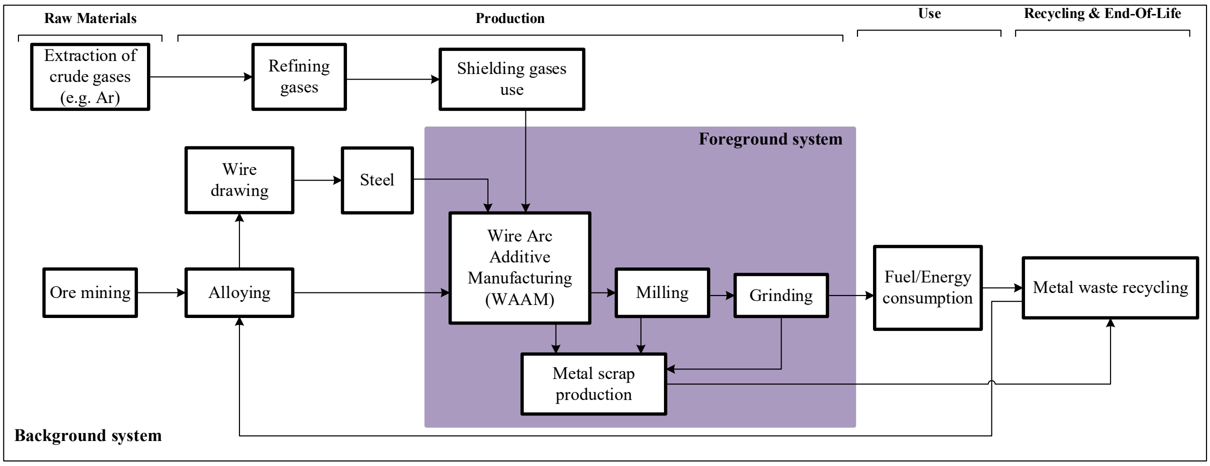

Figure 29: system boundaries of life cycle of wire arc additive manufacturing Gorenje Orodjarna forming tool.

Table 27: characterized results for B-4.2 using ReCiPe2016 (H) midpoint. For each midpoint impact category in light red is highlighted the alternative with the worse impact score. Generally, WAAM has higher environmental impact than CM.

Impact category	Unit	CM	WAAM
Global warming	kg CO_2 eq	5.51E+02	7.28E+02
Stratospheric ozone depletion	kg CFC11 eq	2.15E-04	3.32E-04
Ionizing radiation	kBq Co-60 eq	9.90E+01	2.18E+02
Ozone formation, Human health	kg NO_x eq	1.25E+00	1.59E+00
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.74E+00	1.96E+00
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.27E+00	1.61E+00

Terrestrial acidification	kg SO_2 eq	2.15E+00	2.84E+00
Freshwater eutrophication	kg P eq	4.43E-01	5.94E-01
Marine eutrophication	kg N eq	3.67E-02	3.96E-02
Terrestrial ecotoxicity	kg 1,4-DCB	1.3759E+04	1.3722E+04
Freshwater ecotoxicity	kg 1,4-DCB	1.03E+02	8.65E+01
Marine ecotoxicity	kg 1,4-DCB	1.34E+02	1.14E+02
Human carcinogenic toxicity	kg 1,4-DCB	6.50E+02	5.91E+02
Human non-carcinogenic toxicity	kg 1,4-DCB	9.43E+02	1.08E+03
Land use	m2a crop eq	1.98E+01	2.57E+01
Mineral resource scarcity	kg Cu eq	3.75E+01	3.45E+01
Fossil resource scarcity	kg oil eq	1.33E+02	1.92E+02
Water consumption	m^3	6.90E+00	1.22E+01

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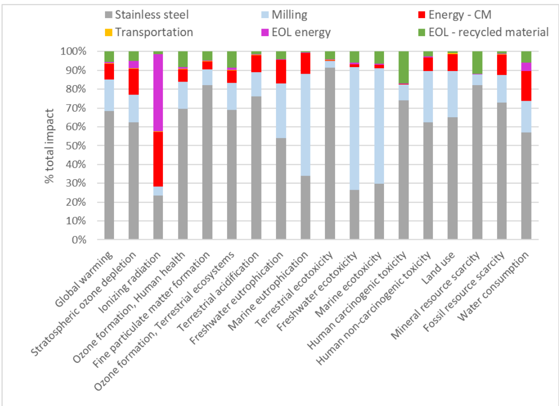

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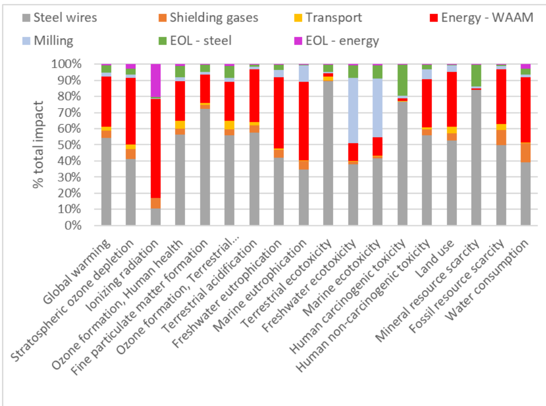

Figure 30: process contribution of Gorenje Orodjarna forming tool demonstrator B4.2 produced with (A) casting; (B) WAAM. Generally in (A) the main contributions come from Milling and Casted stainless steel processes. In (B) often Steel wires contribute the most, except that for Ionizing radiation for which is Energy WAAM the main contribution and Freshwater/Marine ecotoxicity for which also Metal scrap is relevant.

Table 28: summary of sensitivity analysis of Gorenje Orodjarna forming tool demonstrator B4.2. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage	Shielding gas flow rate → From 0.56 kg / kg product to 1.68 kg / kg product	WAAM	13	Weight composite tool	Both	100 (CM) / (AM)
	Scrap rate → from 19% to 22%	WAAM	5	Electricity	CM	6

Table 29: Characterized results of B-4.2 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	1.66E-01	1.72E-01

Ecosystems	1.98E-03	2.56E-03
Resources	1.33E-03	1.76E-03

Life Cycle Costing (LCC)

Table 30: inventory of costs/revenues throughout the whole life cycle of demonstrator B4.2

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 (€/kg)	Recycling disposed product (€/product)	
	Sold scrap from product machining (€/product)	
REVENUE		
Automotive parts selling (€/ yr)	Automotive part price (€/ product)	
	N. automotive part produced (n. parts/ product)	

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)	
Operational (use of cutting tool)		
Repair (€/yr)	Repair cost (€/product)	
	Repair time (n./yr)	
REVENUE-RECYCLABLES		
Recycling - Scrapping value (€/kg)	Recycling disposed product (€/product)	
	Sold scrap from product machining (€/product)	
REVENUE		
Automotive parts selling (€/ yr)	Automotive part price (€/ product)	
	N. automotive part produced (n. parts/ product)	

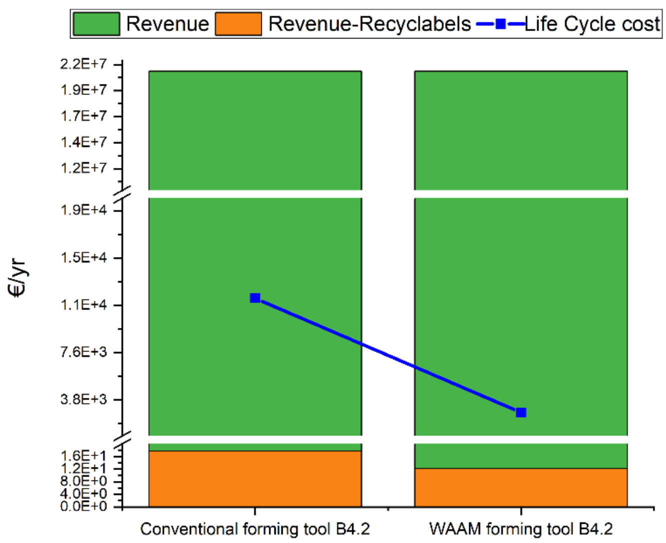

Figure 31: illustration of financial life cycle cost of Gorenje Orodjarna forming tool demonstrator B4.2.

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)	Revenues (€\year)
Conventional forming tool (automotive)	1.20E+04	1.77E+01	2.10E+07
WAAM forming tool (automotive)	2.80E+03	1.22E+01	2.10E+07

Grade2XL

1.1.2.8. Demonstrator B-5

This demonstrator is a cutting tool insert 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.

Life Cycle Assessment (LCA)

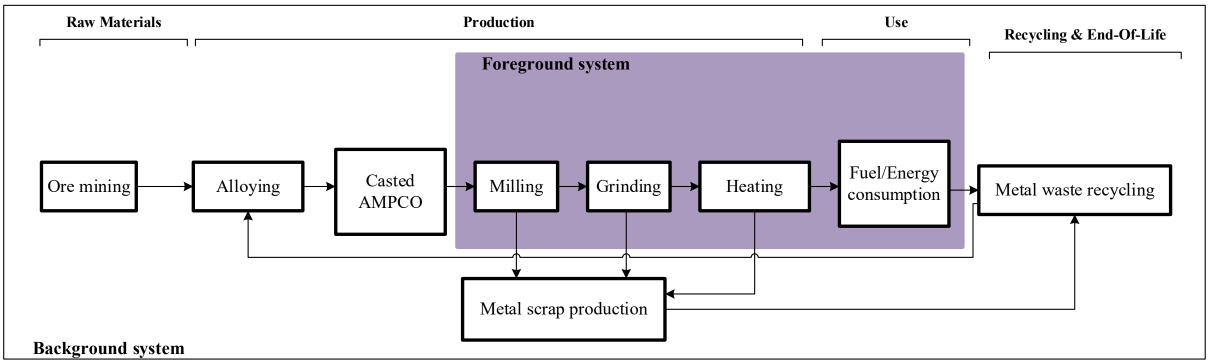

Figure 32: system boundaries of life cycle of conventional manufacturing Gorenje Orodjarna cutting tool demonstrator B5.

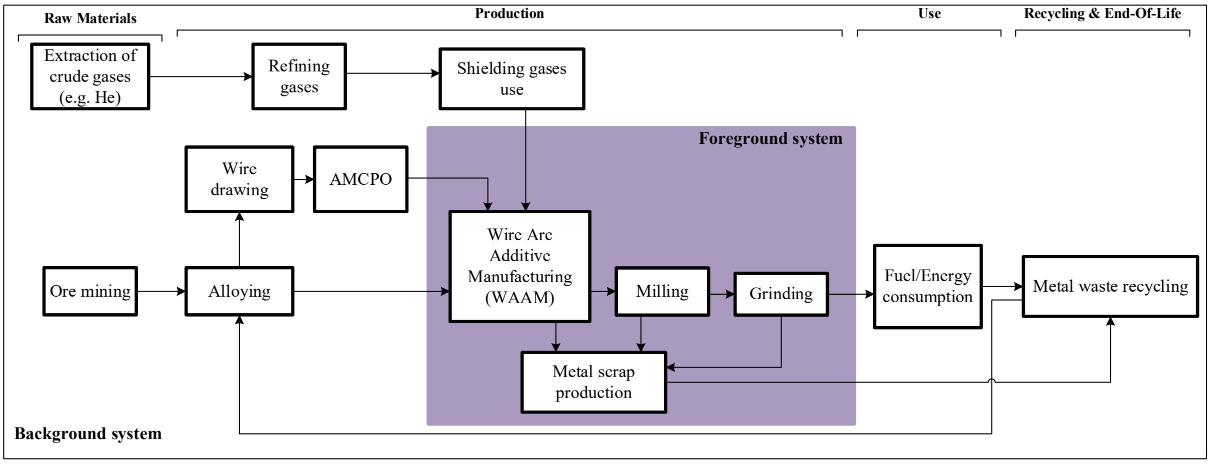

Figure 33: system boundaries of life cycle of wire arc additive manufacturing Gorenje Orodjarna cutting tool demonstrator B5.

Table 31: characterized results for B-5 using ReCiPe2016 (H) midpoint. For each midpoint impact category in light red is highlighted the alternative with the worse impact score. CM is worse than WAAM for all impact categories.

Impact category	Unit	CM	WAAM
Global warming	kg CO_2 eq	7.76E+05	2.37E+05
Stratospheric ozone depletion	kg CFC11 eq	9.11E-01	2.78E-01
Ionizing radiation	kBq Co-60 eq	1.66E+05	5.07E+04
Ozone formation, Human	kg NO_x eq	5.39E+03	1.64E+03
Fine particulate matter	kg $PM_{2.5}$ eq	9.90E+03	3.02E+03
Ozone formation, Terrestrial	kg NO_x eq	5.49E+03	1.67E+03
Terrestrial acidification	kg SO_2 eq	2.93E+04	8.94E+03
Freshwater eutrophication	kg P eq	3.39E+03	1.03E+03

Marine eutrophication	kg N eq	1.04E+02	3.17E+01
Terrestrial ecotoxicity	kg 1,4-DCB	2.23E+08	6.79E+07
Freshwater ecotoxicity	kg 1,4-DCB	2.55E+06	7.77E+05
Marine ecotoxicity	kg 1,4-DCB	3.26E+06	9.94E+05
Human carcinogenic toxicity	kg 1,4-DCB	3.07E+05	9.38E+04
Human non-carcinogenic	kg 1,4-DCB	3.89E+07	1.19E+07
Land use	m2a crop eq	1.53E+05	4.66E+04
Mineral resource scarcity	kg Cu eq	1.46E+05	4.44E+04
Fossil resource scarcity	kg oil eq	2.17E+05	6.64E+04
Water consumption	m^3	2.20E+04	6.72E+03

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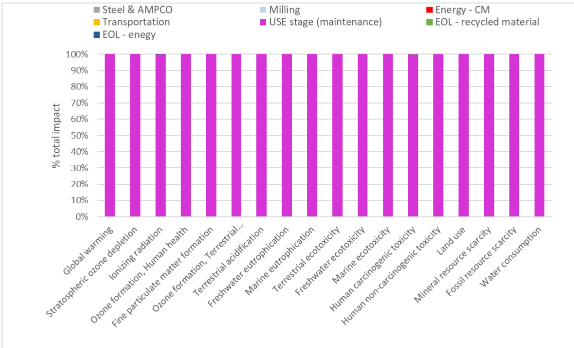

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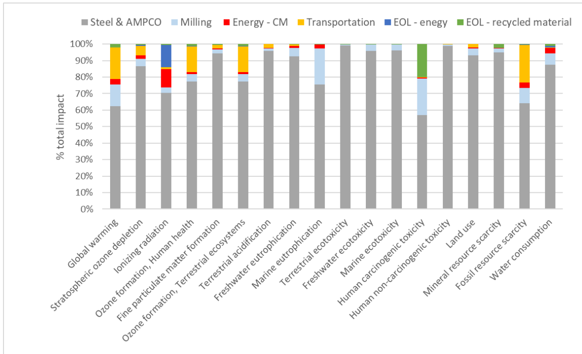

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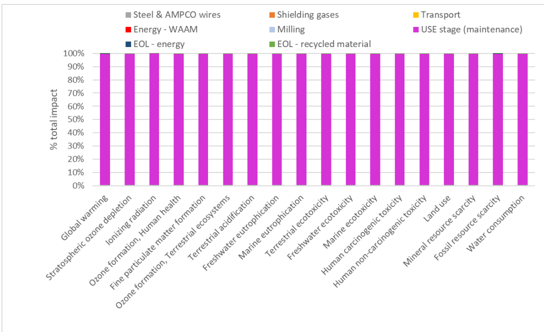

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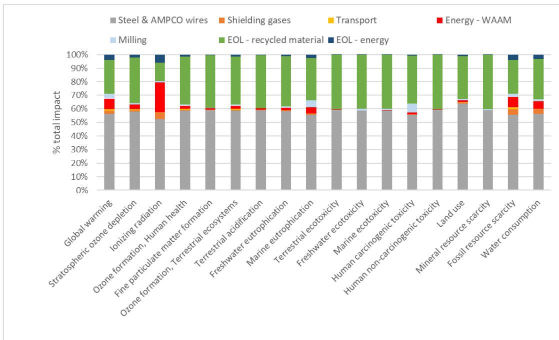

Figure 34: process contribution of Gorenje Orodjarna forming tool demonstrator B5 produced with (A) casting; (B) casting without the maintenance of the tool during the use stage; (C) WAAM; WAAM without the maintenance of the tool during the use stage. When the use stage is excluded for the both scenario, the most contributing process for both alternatives is represented by AMPCO production.

Table 32: summary of sensitivity analysis of Gorenje Orodjarna forming tool demonstrator B5. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage	Shielding gas flow rate → From 0.59 kg / kg product to 1.68 kg / kg product	WAAM	46	Weight composite tool	Both	100 (CM) / (AM)
	Scrap rate → from 19% to 22%	WAAM	9	Electricity (without use stage)	CM	0

Table 33: Characterized results of B-5 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	7.03E+02	2.14E+02
Ecosystems	1.19E+01	3.63E+00
Resources	3.35E+00	1.02E+00

Life Cycle Costing (LCC)

Table 34: inventory of costs/revenues throughout the whole life cycle of demonstrator B5

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 (€/kg)		Recycling disposed product (€/product)
		Sold scrap from product machining (€/product)
REVENUE		
Back face washing drum parts selling (€/ yr)		Back face washing drum part price (€/ product)
		N. back face washing drum part produced (n. parts/ product)

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 (€/kg)	Recycling disposed product (€/product)	
	Sold scrap from product machining (€/product)	
REVENUE		
Back face washing drum parts selling (€/ yr)	Back face washing drum part price (€/ product)	
	N. back face washing drum part produced (n. parts/ product)	

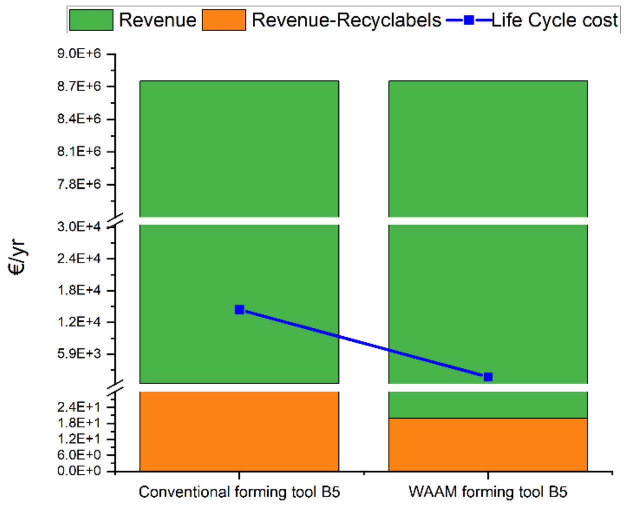

Figure 35: illustration of financial life cycle cost of Gorenje Orodjarna forming tool demonstrator B5.

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)	Revenues (€\year)
Conventional cutting tool (white goods)	1.42E+04	3.61E+02	8.75E+06
WAAM cutting tool (white goods)	1.64E+03	1.99E+01	8.75E+06

1.1.2.9. Demonstrator B-6

This demonstrator is a hot forging die used by Kuznia and it requires frequently repairments. Wire Arc Additive Manufacturing (WAAM) will be used for repair purpose, instead of conventional welding.

Life Cycle Assessment (LCA)

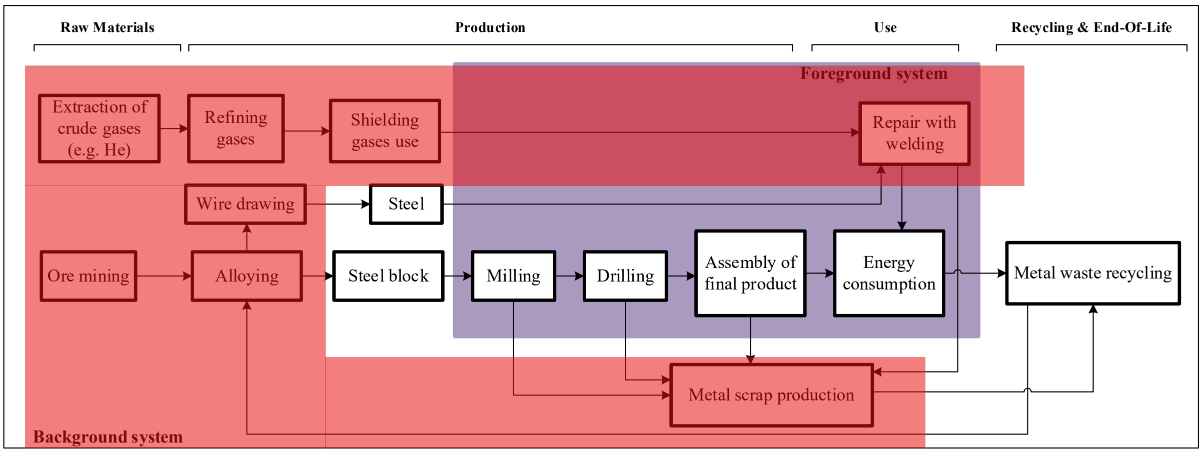

Figure 36: system boundaries of life cycle of conventional manufacturing and wire arc additive manufacturing of Kuznia Jawor hot forging die (repair case). The part highlighted in red includes the processes considered in the LCA-model, since all the others are the same.

Table 35: characterized results for B-6 using ReCiPe2016 (H) midpoint. For each midpoint impact category in light red is highlighted the alternative with the worse impact score. In this case, CM performs worse than WAAM, except for terrestrial ecotoxicity .

Impact category	Unit	CM	WAAM
Global warming	kg CO_2 eq	3.10E+03	6.40E+02
Stratospheric ozone depletion	kg CFC11 eq	1.48E-03	2.92E-04
Ionizing radiation	kBq Co-60 eq	1.29E+03	2.11E+02
Ozone formation, Human	kg NO_x eq	5.99E+00	1.35E+00
Fine particulate matter	kg $PM_{2.5}$ eq	4.82E+00	1.48E+00
Ozone formation, Terrestrial	kg NO_x eq	6.11E+00	1.37E+00
Terrestrial acidification	kg SO_2 eq	1.09E+01	2.40E+00
Freshwater eutrophication	kg P eq	2.88E+00	5.54E-01
Marine eutrophication	kg N eq	2.23E-01	3.96E-02
Terrestrial ecotoxicity	kg 1,4-DCB	7.67E+03	8.39E+03
Freshwater ecotoxicity	kg 1,4-DCB	5.32E+02	2.81E+02
Marine ecotoxicity	kg 1,4-DCB	6.63E+02	3.44E+02
Human carcinogenic toxicity	kg 1,4-DCB	1.02E+03	4.57E+02
Human non-carcinogenic	kg 1,4-DCB	4.28E+03	1.08E+03
Land use	m2a crop eq	1.00E+02	2.22E+01
Mineral resource scarcity	kg Cu eq	3.15E+01	2.35E+01
Fossil resource scarcity	kg oil eq	7.93E+02	1.63E+02
Water consumption	m^3	6.78E+01	1.06E+01

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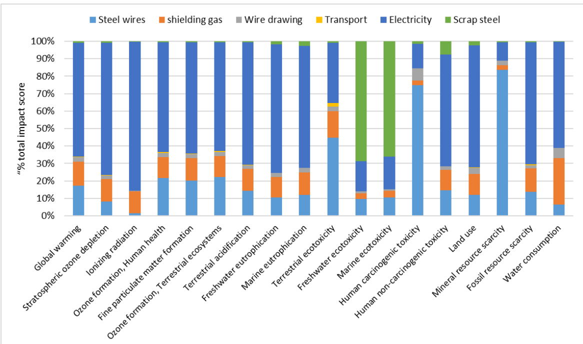

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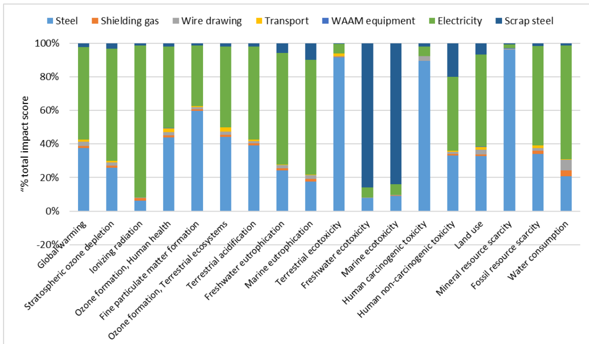

Figure 37: process contribution of Kuznia Jawor hot forging die repaired with (A) conventional welding; (B) WAAM. For both alternatives, the most contributing process generally is the energy consumption for welding, scrap steel for Freshwater and Marine ecotoxicity, and steel wires production for terrestrial ecotoxicity and human carcinogenic toxicity. Then, steel wires production is contributing to fossil resource scarcity and mineral resource scarcity for alternative (A) and (B), respectively.

Table 36: summary of sensitivity analysis of Kuznia Jawor hot forging die repaired. In the table are reported the results for the sensitivity scenarios (on the left), and the one-at-time parameter perturbation (on the right). The cells highlighted in yellow illustrate the sensitive/important parameters or processes (i.e. value ≥ 50%)

LC-stage	Sensitivity scenarios			One-at-time parameter perturbation (+10%)		
	Process	Type of manufacturing	Max relative change %	Process	Type of manufacturing	Max $S_{coefficient}$ %
Manufacturing stage3	Recycling metal scraps	WAAM	2092	Shielding gas	WAAM	3
	144 kg of wire needed	WAAM	200	Electricity	WAAM	91
				Shielding gas	CM	27
				Electricity	CM	85

Table 37: Characterized results of B-6 calculated with ReCiPe2016 (H) endpoint life cycle impact assessment (LCIA) methodology.

Impact category	CM	WAAM
Human health	4.52E-01	1.38E-01
Ecosystems	1.12E-02	2.33E-03
Resources	5.99E-03	1.37E-03

Life Cycle Costing (LCC)

Table 38: 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 (€/kg)	Recycling disposed product (€/product)		Recycling - Scrapping value (€/kg)	Recycling disposed product (€/product)	
	Sold scrap from product machining (€/product)			Sold scrap from product machining (€/product)	
REVENUE			REVENUE		
Lifting tools produced by forging die (€)	Lifting tool price (€)		Lifting tools produced by forging die (€)	Lifting tool price (€)	
	N. lifting tools produced (item/yr)			N. lifting tools produced (item/yr)	
	Lifetime forging die (yr)			Lifetime forging die (yr)	

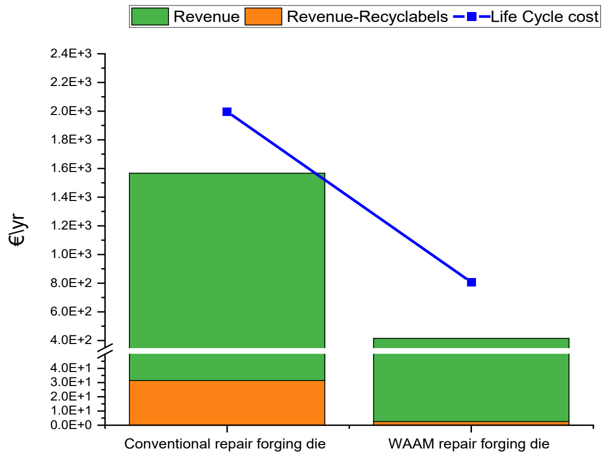

Figure 38: illustration of financial life cycle cost of Kuznia Jawor hot forging die repair.

$$Lifting\ tool\ cost = \frac{cost\ repair\ for\ product\ lifetime}{operational\ lifetime\ repaired\ die}$$

Lifting tool cost (€)	
CM	WAAM
0.61	0.16
	0.37

	Lifecycle costs (€\year)	Revenue-recyclables (€\year)	Revenues (€\year)	Overall gain (€)	Overall gain with WAAM lifting tool 0.37€ (€)
Conventional hot forging die repair	3.54E+05	3.38E+03	3.38E+03	-4.28E+02	
WAAM hot forging die repair	2.44E+05	2.19E+03	2.19E+03	-5.02E+02	3.1E+01

1.1.3. Discussion

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 check, comparison with existing knowledge, and sensitivity analysis (see section 1).

- Data completeness check

Demonstrator	Life Cycle stage	% data availability (CM)	Origin of data	% data availability (WAAM)	Origin of data
A1, A2, B1, B2, B3, B4-1, B4-2, B5, B6	Raw materials	90%	database	90%	database
	Manufacturing	90%	database, literature and primary data	*90%	primary data
	Use	90%	calculated	90%	calculated
	End-of-Life	90%	literature	90%	literature

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

- Comparison with existing knowledge

Table 38 shows some WAAM parameters from Grade2XL demonstrators in comparison to the findings from relevant existing studies (Samruddha Kokare 2023), (Anne C.M. Bekker 2018), (Izhar Hussain Shah 2023). 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	(Anne C.M. Bekker 2018)
0.85	3.07	1	12	Ar	(Izhar Hussain Shah 2023)
	2.46	2			
	2.09	5			
0.41	1.12	0.1208	16	82 % Argon and 18 % CO_2	(Samruddha Kokare 2023)
From 0.74 to 0.93	4	2.5	20	Different proportions of Ar, CO_2 and He depending on the demonstrator	Grade2XL
	2	5			

1.1.4. 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 20% to 99% in relation to conventional options. Main contributing processes for WAAM are: shielding gas, energy consumption during WAAM, and material input use. For conventional manufacturing option the generally the most contributing process is the material input use, and energy for recycling for the impact category Ionizing radiation.
Below in Table 38 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 preliminary LCA and financial LCC for each Grade2XL demonstrator

Demonstrator	Company	Product	Second iteration conclusion
A-1	MAN	Ship propeller (small/ medium/ large)	1) WAAM propeller performs better than casted propeller 2) Linear increase in impact score with the increase of size of MAN´s ship propeller 3) Main contributing life cycle stage: USE STAGE 4) Excluding USE STAGE: a. contributing processes: bronze ingot production and Inconel for casted and WAAM ship propeller, respectively b. contributing substance for global warming: CO2 fossil due to energy consumption in manufacturing of WAAM and bronze production in casting c. Important parameters: Inconel, shielding gases, bronze casting, and recycling rate of metals 5) Not relevant choices:

			a. mould in casting b. changing market location of the ship propeller to Europe 6) Environmental impact score and Lifecycle costs and revenues increase linearly with the size of the ship propeller 7) Costs and Revenues-Recyclables for casted propellers higher than the WAAM 8) Lead time for CM is about 20%-80% higher than WAAM
A-2	EDF	Holding Ring (hydroelectric)	1) WAAM holding ring performs better than conventional manufacturing in 13 out of 18 midpoint impact category 2) CM: steel for casting is the main contributing process, except for Ionizing radiation in which the energy for recycling is the main contributor 3) WAAM: shielding gases and Inox/steel/bronze wires production are the main contributing process 4) Important processes: type of steel, shielding gas and reference flow 5) LCC: costs for CM are approx. 63% higher than WAAM 6) Lead time for CM is about 67% higher than WAAM
B-1	Villeroy & Boch	Bathtub Mould (white goods)	1) WAAM bathtub mould performs better than conventional 2) CM: energy for milling and End-Of-Life are the main contributing process 3) WAAM: shielding gases is the main contributing process, except in toxicity impact categories and mineral resource scarcity in which is steel wires 4) Important processes: shielding gas and reference flow 5) LCC: costs and revenues-recyclables for CM are approx. 99% higher than WAAM
B-2	GKN	Mould for composites (aerospace)	1) CM performs worse than WAAM 2) CM: invar casting is the major contributor, and energy for recycling of the product is the main contribution to the impact category *Ionizing radiation*. When the large is considered the contribution of milling increased 3) WAAM: invar wires is the main contributing process 4) Important processes: shielding gas flow for WAAM and final product weight for CM and WAAM 5) Lifecycle costs and revenues increase linearly with the size of the tool 6) Costs and Revenues-Recyclables for casted tool higher than the WAAM 7) Lead time with WAAM is reduced of 21-67%
B-3	Shapers	Injection Mould (optical fiber closure)	1) WAAM injection mould performs better than conventional for the environmental (LCA) and economic (LCC) life cycle 2) CM: cast steel production, and mould use for Ionizing radiation most contributing 3) WAAM: shielding gases, cast iron production, milling, and injection mould use most contributing 4) Important processes: use stage in conventional and additive manufacturing, and manufacturing process for steel block 5) With WAAM lead time reduction of 45%
B-4.1	Gorenje	Cutting tool (automotive)	1) WAAM performs better than CM 2) CM: casted stainless steel followed by milling are the most contributing processes 3) WAAM: steel wire followed by shielding gas are the most contributing processes 4) For both CM and WAAM in the impact category Ionizing radiation the energy for recycling and manufacturing are contributing the most 5) Important processes: shielding gas flow for WAAM and final product weight for CM and WAAM

			6) Costs and Revenues-Recyclables for casted cutting tool higher than the WAAM 7) Lead time with WAAM is reduced of about 87%
B-4.2		Forming tool- (automotive)	1) WAAM performs worse than CM: casted stainless steel followed by milling are the most contributing processes 2) WAAM: steel wire followed by shielding gas are the most contributing processes 3) For both CM and WAAM in the impact category Ionizing radiation the energy for recycling and manufacturing are contributing the most 4) Important processes: shielding gas flow for WAAM, final product weight for both CM and WAAM, and energy consumption for conventional manufacturing 5) Costs and Revenues-Recyclables for casted forming tool higher than the WAAM 6) Lead time with WAAM is reduced of about 87%
B-5		Cutting tool (white goods)	1) WAAM performs better than CM 2) CM: casted AMPCO production is the most contributing processes, when the use stage is excluded. Indeed, the maintenance of the tool requires high amount of feedstock and thus has a high environmental impact. 3) WAAM: AMPCO wire is the most contributing processes 4) Important processes: shielding gas flow for WAAM and final product weight for CM and WAAM 5) Costs and Revenues-Recyclables for casted cutting tool higher than the WAAM 6) Lead time with WAAM is reduced of about 90%
B-6	Kuznia Jawor	Forging die (repair case)	1) WAAM forging die performs better than conventional for the environmental (LCA) and economic (LCC) life cycle, and the most convenient alternative depends on lifting tool price 2) CM: energy welding and steel wires are the most contributing 3) WAAM: energy WAAM, steel wires and shielding gas are the most contributing 4) Important processes: electricity for both alternatives, and for WAAM also: shielding gas, kg repair material for WAAM and recycling metal scrap

1.2. Future improvements

Deliverable D6.2 is meant to be an assessment of the nine Grade2XL demonstrators sustainability both in environmental and economic terms. By month 42 (August 2023) the results of the Life Cycle Assessment and the financial Life Cycle Costing and the inventory of the demonstrators were updated and more precise thanks to continuous meetings with project partners. In order to mitigate sources of uncertainties in the analysis it is forecasted to include by Deliverable D6.3:

- Further sensitivity scenarios on End-of-Life of the Grade2XL demonstrators;
- Develop a best and worst scenario analysis for each Grade2XL demonstrators;
- Uncertainty analysis (i.e. Monte Carlo) for LCA models;

Moreover, in the table below (Table 39) is presented an additional detailed overview of the missing data for each use case individually. The pending data is predicted to be collected through regular meetings with the end-users (MAN, EDF, Villeroy & Boch, GKN, Orodjarna Gorenje, Kuznia, Shapers), the suppliers (Lincoln Electric, voestalpine Bohler, Air Products, valkWelding) and the WAAM experts (RAMLAB and Naval Group).

Table 41: pending data for each Grade2XL demonstrators

Demonstrator	Company	Product	Second iteration conclusion
A-1	MAN	Ship propeller (small/ medium/ large)	
A-2	EDF	Holding Ring (hydroelectric)	Pending: lead time reduction motivation,
B-1	Villeroy & Boch	Bathtub Mould (white goods)	Pending: concrete amount, production of cooling channels, energy consumption, and differences in the use of the mould, lead time reduction motivation
B-2	GKN	Mould for composites (aerospace)	Pending: aerospace part price (€), general check if LCA data, lead time reduction motivation, quantification of improved heating efficiency with WAAM alternative
B-3	ARKK Shapers	Injection Mould (optical fiber closure)	Pending: optical fiber closure price (€), double check energy consumption use stage, shielding gases cost, conventional manufacturing process for steel block, lead time reduction motivation
B-4.1	Gorenje	Cutting tool (automotive)	Pending: car gusset and back face washing machine drum price (€), lead time reduction motivation, reason why there is no maintenance for B5 produced with WAAM
B-4.2		Forming tool- (automotive)	
B-5		Cutting tool (white goods)	
B-6	Kuznia Jawor	Forging die (repair case)	Pending: repair time, reason for half number repairs with WAAM,

2. References

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3. Appendix A

1.3. Data assumptions

Table 42: summary of assumptions and justifications for each Grade2XL demonstrators

Demonstrator	Company	Product	Assumptions	Justifications	Source
A-1	MAN	Ship propeller (small/ medium/ large)	(1) Ship propeller lifetime: 20 years; (2) 0.01% fuel saving with propeller produced through WAAM; (3) 4 blades for each propeller; (4) 46% lifetime extension for WAAM; (5) Lead time reduction with WAAM from 20% to 80%;	(2) Reduction of cavitation erosion damage; (4) Hardness increase (205/140=1.46);	Estimations made by end-users
A-2	EDF	Holding Ring (hydroelectric)	(1) Holding ring lifetime: 10 years; (2) Maintenance is the same; (3) lead time reduction with WAAM about 67%;		Estimations made by end-users
B-1	Villeroy & Boch	Bathtub Mould (white goods)	(1) Bathtub mould lifetime: 10 years; (2) Maintenance and steel frame is the same; (3) Produce 1,000 bathtubs/yr; (4) Lead time reduction with WAAM from 80% to 82%;		Estimations made by end-users
B-2	GKN	Mould for composites (aerospace)	(1) Composite tool lifetime: 20 years; (2) Maintenance is the same; (3) Different energy consumption during use; (4) Lead time reduction with WAAM from 21% to 67%;	(3) Better heating-cooling system due to the freedom of design of WAAM and possibility to insert more efficient heating system;	Estimations made by end-users
B-3	Shapers	Injection Mould (optical fiber closure)	(1) Injection moulding Injection mould lifetime: 17 years; (2) Reduction of 30% of energy for WAAM mould during cooling step; (3) Produce 1 million parts for car; (4) Lead time reduction with WAAM about 45%;	(2) Cooling channels will be designed in a more efficient way;	Estimations made by end-users
B-4.1	Gorenje	Cutting tool (automotive)	(1) 64% less material due to near-net shape production; (2) WAAM could allow local hardening (maybe less energy		Estimations made by end-users

			consumption); (3) Produce 100,000 pieces of metallic automotive parts; (4) Cutting tool lifetime 7 yr; (5) Lead time reduction 87%;		
B-4.2		Forming tool-(automotive)	(1) 64% less material due to near-net shape production; (2) WAAM could allow local hardening (maybe less energy consumption); (3) Produce 100,000 pieces of metallic automotive parts; (4) Forming tool lifetime 7 yr; (5) Lead time reduction 87%;		Estimations made by end-users
B-5		Cutting tool (white goods)	(1) 94% less high alloyed materials; (2) 65% less material (overall) due to near-net shape production; (3) Produce 100,000 pieces of back washing machine drums; (4) Cutting tool lifetime 5 yr; (5) Lead time reduction 90%; (6) for WAAM is considered that there will not any manteinance;		Estimations made by end-users
B-6	Kuznia Jawor	Forging die (repair case)	(1) Hot forging die lifetime is 2 yr; (2) Steel forging die is the same; (3) Repair with CM is once a month, with WAAM is once every two months; (4) Repair time reduction with WAAM from 39% to 94% in 2 years product lifetime;	(3) Enhanced wear and temperature resistance due to WAAM graded repair;	Estimations made by end-users

1.4. Unit processes of Life Cycle Inventory (LCI)

Below are reported the unit processes for each Grade2XL demonstrator. Here are included only the unit processes created for the preliminary assessment, but not the one from the database or the one that were slightly modified from the ones available in ecoinvent. In this LCI all the processes were balanced in relation to 1 piece of product or 1 kg of the relative process or product.
All the unit processes that are the same for the same or similar case of study (e.g. A-1, B-2, B4.1/2) are neglected.
Moreover, for the transport of the product the following formula was used:

$$T = \frac{w_{t_{product}} \times t_{distance} \times 1\ kg\ product}{w_{kg_{product}}}$$

in which:

T = transport $\left[\frac{tkm}{kg}\right]$
$w_{t\_product}$ *= total weight product produced a year* $[tonnes]$
$t_{distance}$ *= total distance from supplier to retailer* $[km]$
$w_{kg\_product}$ *= total weight product produced a year* $[kg]$

Demonstrator A-1

Table 43: Inventory for unit process "1 piece of small casted propeller" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of small casted propeller	1	p	
Inputs from technosphere: materials/fuels			
CASTING ship propeller small	1893	kg	Industrial partner
POST-TREATMENT casted ship propeller small	1893	kg	Industrial partner
USE casted ship propeller small	1893	kg	Industrial partner
EOL casted ship propeller small	1893	kg	Industrial partner

Table 44: Inventory for unit process "CASTING ship propeller small" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CASTING ship propeller small	1	kg	
Inputs from technosphere: materials/fuels			
_Casting, bronze {GLO}| market for | APOS, U	1.22	kg	Industrial partner

Table 45: Inventory for unit process "POST-TREATMENT casted ship propeller small" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT casted ship propeller small	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	1.43	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	0.102	kWh	Industrial partner
Electricity, medium voltage {ES}| market for | APOS, U	0.102	kWh	Industrial partner
Electricity, medium voltage {PT}| market for | APOS, U	0.102	kWh	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	9.46	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.19	tkm	Industrial partner
Emissions to air			
Benzene	4.08E-6	kg	(Dalquist, S., and Gutowski, T. 2004)
Formaldehyde	3.57E-6	kg	(Dalquist, S., and Gutowski, T. 2004)
Outputs to technosphere: Waste treatment			
Casted ship propeller small, post-treatment waste recycling	1.43	kg	Industrial partner

Table 46: Inventory for unit process "USE casted ship propeller small" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
USE casted ship propeller small	1	kg	
Inputs from technosphere: materials/fuels			
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	1.38E+11	tkm	Industrial partner

Table 47: Inventory for unit process "EOL casted ship propeller small " for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL casted ship propeller small	1	kg	
Outputs to technosphere: Waste treatment			
Casted ship propeller small, waste recycling	1	kg	Industrial partner

Table 48: Inventory for unit process " Casted ship propeller small, waste recycling " for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
Casted ship propeller small, waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Bronze {GLO}| market for | APOS, U	0.8	kg	Industrial partner
Inputs from technosphere: materials/fuels			
_Recycling casted bronze {GLO}| market for | APOS, U	1	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.19	tkm	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	9.46	tkm	Industrial partner

Table 49: Inventory for unit process " 1 piece of medium casted propeller" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of medium casted propeller	1	p	
Inputs from technosphere: materials/fuels			
CASTING ship propeller medium	5293	kg	Industrial partner
POST-TREATMENT casted ship propeller medium	5293	kg	Industrial partner
USE casted ship propeller medium	5293	kg	Industrial partner
EOL casted ship propeller medium	5293	kg	Industrial partner

Table 50: Inventory for unit process "POST-TREATMENT casted ship propeller medium" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT casted ship propeller medium	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	1.17	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	0.102	kWh	Industrial partner
Electricity, medium voltage {ES}| market for | APOS, U	0.102	kWh	Industrial partner
Electricity, medium voltage {PT}| market for | APOS, U	0.102	kWh	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	9.46	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.19	tkm	Industrial partner
Emissions to air			
Benzene	4.08E-6	kg	(Dalquist, S., and Gutowski, T. 2004)
Formaldehyde	3.57E-6	kg	(Dalquist, S., and Gutowski, T. 2004)
Outputs to technosphere: Waste treatment			
Casted ship propeller medium, post-treatment waste recycling	1.17	kg	Industrial partner

Table 51: Inventory for unit process " 1 piece of large casted propeller" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of large casted propeller	1	p	
Inputs from technosphere: materials/fuels			
CASTING ship propeller large	10293	kg	Industrial partner
POST-TREATMENT casted ship propeller large	10293	kg	Industrial partner
USE casted ship propeller large	10293	kg	Industrial partner
EOL casted ship propeller large	10293	kg	Industrial partner

Table 52: Inventory for unit process "POST-TREATMENT casted ship propeller large" for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT casted ship propeller large	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	1.03	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	0.102	kWh	Industrial partner
Electricity, medium voltage {ES}| market for | APOS, U	0.102	kWh	Industrial partner
Electricity, medium voltage {PT}| market for | APOS, U	0.102	kWh	Industrial partner

Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	9.46	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.19	tkm	Industrial partner
Emissions to air			
Benzene	4.08E-6	kg	(Dalquist, S., and Gutowski, T. 2004)
Formaldehyde	3.57E-6	kg	(Dalquist, S., and Gutowski, T. 2004)
Outputs to technosphere: Waste treatment			
Casted ship propeller large, post-treatment waste recycling	1.03	kg	Industrial partner

Table 53: Inventory for unit process " 1 piece of small WAAM propeller" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of small WAAM propeller	1	p	
Inputs from technosphere: materials/fuels			
WAAM ship propeller small	903	kg	Industrial partner
POST-TREATMENT waam ship propeller small	903	kg	Industrial partner
USE waam ship propeller small	903	kg	Industrial partner
EOL waam ship propeller small	903	kg	Industrial partner

Table 54: Inventory for unit process "WAAM ship propeller small" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM ship propeller small	1	kg	
Inputs from technosphere: materials/fuels			
_AM80 Wire drawing (low-alloyed steel) {DE} | processing | Conseq,	0.62	kg	Industrial partner
_AM625 Wire drawing (nickel-based) {DE} | processing | Conseq, U	0.26	kg	Industrial partner
FERROMAX plus, S.3	0.68	kg	Industrial partner
ALLUMAX plus, S.3	0.59	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1	kg	Industrial partner
_welding fumes per kg deposited Inconel	0.26	kg	Industrial partner
_welding fumes per kg deposited Steel	0.62	kg	Industrial partner
WAAM equipment	2.92E-7	P	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	5.99	kWh	Industrial partner
Electricity, medium voltage {KR}| market for | APOS, U	5.99	kWh	Industrial partner

Table 55: Inventory for unit process "WAAM equipment" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM equipment	1	p	
Inputs from technosphere: materials/fuels			
Computer, laptop {GLO}| market for | Conseq, U	1	P	Industrial partner
Electronics, for control units {GLO}| market for | Conseq, U	260	kg	Industrial partner
Reinforcing steel {GLO}| market for | Conseq, U	7411	kg	Industrial partner
Tin plated chromium steel sheet, 2 mm {GLO}| market for | Conseq, U	6.75E1	kg	Industrial partner
Outputs to technosphere: Waste and emissions to treatment			
Electronics scrap from control units (waste treatment) {RER}| treatment of | Conseq, U	260	kg	Industrial partner
_Steel scrap, post-consumer {GLO}| market for steel scrap, post-consumer | Conseq, U	7411	kg	Industrial partner

Table 56: Inventory for unit process "POST-TREATMENT waam ship propeller small" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT waam ship propeller small	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	0.78	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	3.45	kWh	Industrial partner
Electricity, medium voltage {KR}| market for | APOS, U	3.45	kWh	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	21.1	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.11	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Casted ship propeller small, post-treatment waste recycling	0..78	kg	Industrial partner

Table 57: Inventory for unit process "USE waam ship propeller small" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
USE waam ship propeller small	1	kg	
Inputs from technosphere: materials/fuels			
_WAAM Transport freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	1.38E+11	tkm	Industrial partner

Table 58: Inventory for unit process " EOL waam ship propeller small" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL waam ship propeller small	1	kg	
Outputs to technosphere: Waste treatment			
WAAM ship propeller small, waste recycling	1	kg	Industrial partner

Table 59: Inventory for unit process " WAAM ship propeller small, waste recycling " for Grade2XL demonstrator A-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM ship propeller small, waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Steel, low-alloyed {GLO}| market for | Cut-off, U	0.674	kg	Industrial partner
Inconel 625	0.27	kg	Industrial partner
Inputs from technosphere: materials/fuels			
Electricity, medium voltage {CN}| market for | APOS, U	1.74	kWh	Industrial partner
Electricity, medium voltage {KR}| market for | APOS, U	1.74	kWh	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.11	tkm	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	21.1	tkm	Industrial partner

Table 60: Inventory for unit process " 1 piece of medium WAAM propeller" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of medium WAAM propeller	1	p	
Inputs from technosphere: materials/fuels			
WAAM ship propeller medium	2520	kg	Industrial partner
POST-TREATMENT waam ship propeller medium	2520	kg	Industrial partner
USE waam ship propeller medium	2520	kg	Industrial partner
EOL waam ship propeller medium	2520	kg	Industrial partner

Table 61: Inventory for unit process " POST-TREATMENT waam ship propeller medium " for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT waam ship propeller medium	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	0.618	kg	Industrial partner

Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	3.45	kWh	Industrial partner
Electricity, medium voltage {KR}| market for | APOS, U	3.45	kWh	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	21.1	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.11	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Casted ship propeller small, post-treatment waste recycling	0.168	kg	Industrial partner

Table 62: Inventory for unit process "1 piece of large WAAM propeller" for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of large WAAM propeller	1	p	
Inputs from technosphere: materials/fuels			
WAAM ship propeller large	4891	kg	Industrial partner
POST-TREATMENT waam ship propeller large	2520	kg	Industrial partner
USE waam ship propeller large	2520	kg	Industrial partner
EOL waam ship propeller large	2520	kg	Industrial partner

Table 63: Inventory for unit process " POST-TREATMENT waam ship propeller medium " for Grade2XL demonstrator A-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT waam ship propeller medium	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	0.538	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {CN}| market for | APOS, U	3.45	kWh	Industrial partner
Electricity, medium voltage {KR}| market for | APOS, U	3.45	kWh	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	21.1	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.11	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Casted ship propeller small, post-treatment waste recycling	0.538	kg	Industrial partner

Demonstrator A-2

Table 64: Inventory for unit process " 1 piece EDF holding ring" for Grade2XL demonstrator A-2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece EDF holding ring	1	p	

Inputs from technosphere: materials/fuels			
CASTING holding ring	290	kg	Industrial partner
POST-TREATMENT casted holding ring	290	kg	Industrial partner
EOL casted holding ring	290	kg	Industrial partner

Table 65: Inventory for unit process " CASTING holding ring " for Grade2XL demonstrator A-2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CASTING holding ring	1	kg	
Inputs from technosphere: materials/fuels			
_Casting, steel, lost-wax with one-use mould same elec {GLO}| market for | APOS, U	1.1	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	1.09	kWh	Industrial partner
Heat, district or industrial, natural gas {RER}| market group for | APOS, U	19.62	MJ	Industrial partner
Heat, district or industrial, other than natural gas {RER}| market group for | APOS, U	28.25	MJ	Industrial partner

Table 66: Inventory for unit process " POST-TREATMENT casted holding ring" for Grade2XL demonstrator A-2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT casted holding ring	1	kg	
Inputs from technosphere: materials/fuels			
Cast iron removed by milling, average {GLO}| market for | APOS, U	0.1	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	0.25	kWh	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.8	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap copper (waste treatment) {GLO}| market for scrap copper | APOS, U	0.1	kg	Industrial partner

Table 67: Inventory for unit process " EOL casted holding ring" for Grade2XL demonstrator A-2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL casted holding ring	1	kg	
Outputs to technosphere: Waste treatment			
EDF CM, waste recycling	1	kg	Industrial partner

Table 68: Inventory for unit process " EDF CM, waste recycling " for Grade2XL demonstrator A-2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL casted ship propeller small	1	kg	
Outputs to technosphere: Avoided products			
Steel, low-alloyed {GLO}| market for | Cut-off, U	0.9	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	3.67	kWh	(Yellishetty, M., Mudd, G. M., Ranjith, P. G., and Tharumarajah, A. 2011)

Table 69: Inventory for unit process "1 piece of WAAM holding ring" for Grade2XL demonstrator A-2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of small WAAM propeller	1	p	
Inputs from technosphere: materials/fuels			
WAAM holding ring	489.7	kg	Industrial partner
POST-TREATMENT waam holding ring	489.7	kg	Industrial partner
EOL waam holding ring	489.7	kg	Industrial partner

Table 70: Inventory for unit process " WAAM holding ring " for Grade2XL demonstrator A-2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM holding ring	1	kg	
Inputs from technosphere: materials/fuels			
_AM316L Wire drawing (austenitic steel) {DE} | processing | Conseq, U, 2023	0.215	kg	Industrial partner
Bronze {GLO}| market for | APOS, U	0.05	kg	Industrial partner
_AM80 Wire drawing (low-alloyed steel) {DE} | processing | Conseq, U, 2023	1.18	kg	Industrial partner
FERROMAX plus, S.3	0.68	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1.04	kg	Industrial partner
INNOMAX plus, S.3	0.56	kg	Industrial partner
_welding fumes per kg deposited AM316L | from voestalpine, 2023	0.215	kg	Industrial partner
_welding fumes per kg deposited AM80 | from voestalpine, 2023	1.18	kg	Industrial partner
WAAM equipment, 2023	2.92E-7	P	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	5.79	kWh	Industrial partner

Table 71: Inventory for unit process "POST-TREATMENT waam holding ring" for Grade2XL demonstrator A-2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT waam holding ring	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	0.003	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.284	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	2.65	kWh	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.09	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap copper (waste treatment) {GLO}| market for scrap copper | APOS, U	0.331	kg	Industrial partner

Table 72: Inventory for unit process "EOL waam holding ring" for Grade2XL demonstrator A-2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL waam holding ring	1	kg	
Outputs to technosphere: Waste treatment			
EDF CM, waste recycling	1	kg	Industrial partner

Demonstrator B-1

Table 73: Inventory for unit process " 1 piece of bathtub mould" for Grade2XL demonstrator B-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of bathtub mould	1	p	
Inputs from technosphere: materials/fuels			
CM bathtub mould	1627	kg	Industrial partner
USE bathtub mould	1627	kg	Industrial partner
POST-TREATMENT bathtub mould	1627	kg	Industrial partner
EOL bathtub mould	1627	kg	Industrial partner

Table 74: Inventory for unit process " CM bathtub mould " for Grade2XL demonstrator B-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM bathtub mould	1	kg	
Inputs from technosphere: materials/fuels			
_Casting, bronze with one-use mould same elec {GLO}| market for | APOS, U	0.268	kg	Industrial partner
_Copper steel pipe {GLO}| market for | APOS, U	0.00823	kg	Industrial partner
Ferronickel, 25% Ni {GLO}| market for | APOS, U	0.724	kg	Industrial partner
Selective coat, aluminium sheet, nickel pigmented aluminium oxide {GLO}| market for | APOS, U	0.724	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {Canada without Quebec}| market group for | APOS, U	0.402	kWh	Industrial partner

Table 75: Inventory for unit process " POST-TREATMENT bathtub mould " for Grade2XL demonstrator B-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT bathtub mould	1	kg	
Inputs from technosphere: materials/fuels			
_Cast iron removed by milling, average {GLO}| market for | APOS, U	0.11	kg	Industrial partner
_Aluminium removed by milling, small parts {GLO}| market for | APOS, U	0.61	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {Canada without Quebec}| market group for | APOS, U	40.7	kWh	Industrial partner
Electricity, medium voltage {PT}| market for | APOS, U	10.4	kWh	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.1335	tkm	Industrial partner
Transport, freight, aircraft, unspecified {GLO}| market for transport, freight, aircraft, unspecified | APOS, U	6.052	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap copper (waste treatment) {GLO}| market for scrap copper | APOS, U	0.11	kg	Industrial partner
Aluminium scrap, post-consumer {GLO}| market for | APOS, U	0.61	kg	Industrial partner

Table 76: Inventory for unit process " EOL bathtub mould " for Grade2XL demonstrator B-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL bathtub mould	1	kg	
Outputs to technosphere: Waste treatment			
CM_Bathtub mould, waste recycling	1	kg	Industrial partner

Table 77: Inventory for unit process " CM_Bathtub mould, waste recycling " for Grade2XL demonstrator B-1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM_Bathtub mould, waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Bronze {GLO}| market for | APOS, U	0.0159	kg	Industrial partner
Aluminium, cast alloy {GLO}| market for | APOS, U	0.331	kg	Industrial partner
Copper {GLO}| market for | APOS, U	0.00308	kg	Industrial partner
Ferronickel, 25% Ni {GLO}| market for | APOS, U	0.65	kg	Industrial partner
Inputs from technosphere: electricity/heat			
_Casting, bronze {GLO}| market for | APOS, U	1	kg	Industrial partner

Table 78: Inventory for unit process " 1 piece of bathtub mould - WAAM " for Grade2XL demonstrator B-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of small WAAM propeller	1	p	
Inputs from technosphere: materials/fuels			
WAAM bathtub mould	1370	kg	Industrial partner
POST-TREATMENT bathtub mould - WAAM	1370	kg	Industrial partner
EOL bathtub mould - WAAM	1370	kg	Industrial partner

Table 79: Inventory for unit process " WAAM bathtub mould " for Grade2XL demonstrator B-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM bathtub mould	1	kg	
Inputs from technosphere: materials/fuels			
_AM316L Wire drawing (austenitic steel) {DE} | processing | Conseq, U	0.144	kg	Industrial partner
FERROMAX plus, S.3	0.036	kg	Industrial partner
_AM80 Wire drawing (low-alloyed steel) {DE} | processing | Conseq, U	0.406	kg	Industrial partner
_welding fumes per kg deposited AM80 | from voestalpine	0.7	kg	Industrial partner
_welding fumes per kg deposited AM316L | from voestalpine	0.3	kg	Industrial partner
WAAM equipment	2.92E-7	p	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	5.04	kWh	Industrial partner

Table 80: Inventory for unit process "POST-TREATMENT bathtub mould - WAAM" for Grade2XL demonstrator B-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT bathtub mould - WAAM	1	kg	
Inputs from technosphere: materials/fuels			
Steel removed by milling, average {GLO}| market for | APOS, U	0.028	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {NL}| market for | APOS, U	2.73	kWh	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.4	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel {GLO}| market for | APOS, U	0.028	kg	Industrial partner

Table 81: Inventory for unit process "EOL bathtub mould - WAAM" for Grade2XL demonstrator B-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL bathtub mould - WAAM	1	kg	
Outputs to technosphere: Waste treatment			
WAAM_Bathtub mould, waste recycling	1	kg	Industrial partner

Table 82: Inventory for unit process " WAAM_Bathtub mould, waste recycling " for Grade2XL demonstrator B-1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM_Bathtub mould, waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Steel, low-alloyed {GLO}| market for | APOS, U	1	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	3.47	kWh	(Yellishetty, M., Mudd, G. M., Ranjith, P. G., and Tharumarajah, A. 2011)

Demonstrator B-3

Table 83: Inventory for unit process "1 piece of injection mould" for Grade2XL demonstrator B-3 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of injection mould	1	p	
Inputs from technosphere: materials/fuels			
CM injection mould	3374	kg	Industrial partner

USE injection mould	3374	kg	Industrial partner
EOL injection mould	3374	kg	Industrial partner

Table 84: Inventory for unit process " CM injection mould" for Grade2XL demonstrator B-3 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM injection mould	1	kg	
Inputs from technosphere: materials/fuels			
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.193	kg	Industrial partner
_Steel removed by drilling, conventional {GLO}| market for | APOS, U	0.0967	kg	Industrial partner
Casting, steel, lost-wax {GLO}| market for | APOS, U	1.29	kg	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	0.3	tkm	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.307	tkm	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	10.7	kWh	Industrial partner
Electricity, medium voltage {RER}| market group for | APOS, U	1.089921526	kWh	Industrial partner
Heat, district or industrial, natural gas {RER}| market group for | APOS, U	19.62015695	MJ	Industrial partner
Heat, district or industrial, other than natural gas {RER}| market group for | APOS, U	28.25325201	MJ	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.29	kg	Industrial partner

Table 85: Inventory for unit process " USE injection mould " for Grade2XL demonstrator B-3 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
USE injection mould	1	kg	
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	33.5	kWh	Industrial partner

Table 86: Inventory for unit process " EOL injection mould " for Grade2XL demonstrator B-3 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL injection mould	1	kg	
Outputs to technosphere: Waste treatment			
Injection mould CM, waste recycling	1	kg	Industrial partner

Table 87: Inventory for unit process " Injection mould CM, waste recycling " for Grade2XL demonstrator B-3 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
Injection mould CM, waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Steel, low-alloyed {GLO}| market for | APOS, U	1	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	3.67	kWh	(Yellishetty, M., Mudd, G. M., Ranjith, P. G., and Tharumarajah, A. 2011)

Table 88: Inventory for unit process " 1 piece of injection mould - WAAM " for Grade2XL demonstrator B-3 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of injection mould - WAAM	1	p	
Inputs from technosphere: materials/fuels			
WAAM injection mould	1849	kg	Industrial partner
POST-TREATMENT injection mould - WAAM	1849	kg	Industrial partner
USE injection mould - WAAM	1849	kg	Industrial partner
EOL injection mould -WAAM	1849	kg	Industrial partner

Table 89: Inventory for unit process " WAAM injection mould" for Grade2XL demonstrator B-3 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM injection mould	1	kg	
Inputs from technosphere: materials/fuels			
Steel, low-alloyed {GLO}| market for | APOS, U	0.27	kg	Industrial partner
Cast iron {GLO}| market for | APOS, U	0.73	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.3	tkm	Industrial partner
FERROMAX plus, S.3	0.16	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	0.27	kg	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	0.3	tkm	Industrial partner
WAAM equipment	2.92E-7	p	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	1.3	kWh	Industrial partner

Table 90: Inventory for unit process "POST-TREATMENT injection mould - WAAM" for Grade2XL demonstrator B-3 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
POST-TREATMENT injection mould - WAAM	1	kg	
Inputs from technosphere: materials/fuels			
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.008	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	6.69	kWh	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.51	tkm	Industrial partner
Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | APOS, U	0.2	tkm	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel {GLO}| market for | APOS, U	0.008	kg	Industrial partner

Table 91: Inventory for unit process " USE injection mould - WAAM" for Grade2XL demonstrator B-3 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
USE injection mould - WAAM	1	kg	
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {FR}| market for | APOS, U	36.2	kWh	Industrial partner

Table 92: Inventory for unit process " EOL injection mould -WAAM" for Grade2XL demonstrator B-3 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL injection mould -WAAM	1	kg	
Outputs to technosphere: Waste treatment			
Injection mould WAAM, waste recycling	1	kg	Industrial partner

Table 93: Inventory for unit process " Injection mould WAAM, waste recycling " for Grade2XL demonstrator B-3 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
Injection mould WAAM, waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Steel, low-alloyed {GLO}| market for | APOS, U	1	kg	Industrial partner

Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	3.67	kWh	(Yellishetty, M., Mudd, G. M., Ranjith, P. G., and Tharumarajah, A. 2011)

Demonstrator B4.1

Table 94: Inventory for unit process " 1 piece of cutting tool B4.1" for Grade2XL demonstrator B-4.1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of cutting tool B4.1	1	p	
Inputs from technosphere: materials/fuels			
CM cutting tool B4.1	9.5	kg	Industrial partner
EOL cutting tool B4.1	9.5	kg	Industrial partner
USE cutting tool B4.1	9.5	kg	Industrial partner

Table 95: Inventory for unit process "CM cutting tool B4.1" for Grade2XL demonstrator B-4.1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM cutting tool B4.1	1	kg	
Inputs from technosphere: materials/fuels			
Steel, chromium steel 18/8 {GLO}| market for | APOS, U	1.56	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.56	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.13	tkm	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	11	kWh	Industrial partner
Emissions to air			
Iron dust	1.08E-06	kg	Industrial partner
Water (evapotranspiration)	7.28E-6	kg	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.56	kg	Industrial partner

Table 96: Inventory for unit process " EOL cutting tool B4.1" for Grade2XL demonstrator B-4.1 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL cutting tool B4.1	1	kg	
Outputs to technosphere: Waste treatment			
Injection mould CM, waste recycling	1	kg	Industrial partner

Table 97: Inventory for unit process " 1 piece of WAAM cutting tool B4.1" for Grade2XL demonstrator B-4.1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of WAAM cutting tool B4.1	1	p	
Inputs from technosphere: materials/fuels			
WAAM cutting tool B4.1	14	kg	Industrial partner
EOL WAAM cutting tool B4.1	14	kg	Industrial partner
USE WAAM cutting tool B4.1	14	kg	Industrial partner

Table 98: Inventory for unit process " WAAM cutting tool B4.1" for Grade2XL demonstrator B-4.1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM cutting tool B4.1	1	kg	
Inputs from technosphere: materials/fuels			
Steel, chromium steel 18/8 {GLO}| market for | APOS, U	1.45	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1.45	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.26	kg	Industrial partner
INNOMAX plus, S.3	0.56	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	1.93	tkm	Industrial partner
WAAM equipment	2.92E-7	p	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	9.97	kWh	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.45	kg	Industrial partner

Table 99: Inventory for unit process " EOL injection mould -WAAM" for Grade2XL demonstrator B-4.1 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL WAAM cutting tool B4.1	1	kg	
Outputs to technosphere: Waste treatment			
Injection mould CM, waste recycling	1	kg	Industrial partner

Demonstrator B4.2

Table 100: Inventory for unit process " 1 piece of forming tool B4.2" for Grade2XL demonstrator B-4.2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of forming tool B4.2	1	p	
Inputs from technosphere: materials/fuels			
CM forming tool B4.2	61.2	kg	Industrial partner
EOL forming tool B4.2	61.2	kg	Industrial partner
USE forming tool B4.2	61.2	kg	Industrial partner

Table 101: Inventory for unit process " CM forming tool B4.2" for Grade2XL demonstrator B-4.2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM cutting tool B4.1	1	kg	
Inputs from technosphere: materials/fuels			
Steel, chromium steel 18/8 {GLO}| market for | APOS, U	1.41	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.41	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.13	tkm	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	2.27	kWh	Industrial partner
Emissions to air			
Iron dust	1.08E-06	kg	Industrial partner
Water (evapotranspiration)	7.28E-6	kg	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.41	kg	Industrial partner

Table 102: Inventory for unit process " EOL forming tool B4.2" for Grade2XL demonstrator B-4.2 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL forming tool B4.2	1	kg	
Outputs to technosphere: Waste treatment			
Injection mould CM, waste recycling	1	kg	Industrial partner

Table 103: Inventory for unit process " 1 piece of WAAM forming tool B4.2" for Grade2XL demonstrator B-4.2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of WAAM forming tool B4.2	1	p	

Inputs from technosphere: materials/fuels			
WAAM forming tool B4.2	67	kg	Industrial partner
EOL WAAM forming tool B4.2	67	kg	Industrial partner
USE WAAM forming tool B4.2	67	kg	Industrial partner

Table 104: Inventory for unit process " WAAM forming tool B4.2" for Grade2XL demonstrator B-4.2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM forming tool B4.2	1	kg	
Inputs from technosphere: materials/fuels			
Steel, chromium steel 18/8 {GLO}| market for | APOS, U	1.26	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1.26	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.07	kg	Industrial partner
INNOMAX plus, S.3	0.56	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	1.93	tkm	Industrial partner
WAAM equipment	2.92E-7	p	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	9.97	kWh	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.26	kg	Industrial partner

Table 105: Inventory for unit process " EOL WAAM forming tool B4.2" for Grade2XL demonstrator B-4.2 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL WAAM forming tool B4.2	1	kg	
Outputs to technosphere: Waste treatment			
Injection mould CM, waste recycling	1	kg	Industrial partner

Demonstrator B5

Table 106: Inventory for unit process " 1 piece of cutting tool B5" for Grade2XL demonstrator B-5 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of cutting tool B5	1	p	
Inputs from technosphere: materials/fuels			
CM cutting tool B5	87.6	kg	Industrial partner
USE cutting tool B5	87.6	kg	Industrial partner
EOL cutting tool B5	87.6	kg	Industrial partner

Table 107: Inventory for unit process '" CM cutting tool B5" for Grade2XL demonstrator B-5 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM cutting tool B5	1	kg	
Inputs from technosphere: materials/fuels			
_Casting, bronze with one-use mould {GLO}| market for | APOS, U	1.95	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.95	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.13	tkm	Industrial partner
Transport, freight, aircraft, unspecified {GLO}| market for transport, freight, aircraft, unspecified | APOS, U	7.5	tkm	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	2.55	kWh	Industrial partner
Emissions to air			
Iron dust	1.08E-06	kg	Industrial partner
Water (evapotranspiration)	7.28E-6	kg	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.95	kg	Industrial partner

Table 108: Inventory for unit process " USE cutting tool B5" for Grade2XL demonstrator B-5 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
USE cutting tool B5	1	kg	
Inputs from technosphere: materials/fuels			
_Casting, bronze with one-use mould {GLO}| market for | APOS, U	850	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {SI}| market for | APOS, U	1.86E3	kWh	Industrial partner
Emissions to air			
Aluminium, fume or dust	1.08E-06	kg	Industrial partner

Table 109: Inventory for unit process " EOL cutting tool B5" for Grade2XL demonstrator B-5 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL cutting tool B5	1	kg	
Outputs to technosphere: Waste treatment			
Casted AMPCO waste recycling	1	kg	Industrial partner

Table 110: Inventory for unit process " Casted AMPCO waste recycling " for Grade2XL demonstrator B-5 produced with conventional manufacturing (CM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
Casted AMPCO waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Bronze {GLO}| market for | APOS, U	1	kg	Industrial partner
Inputs from technosphere: electricity/heat			
_Recycling casted bronze bronze {GLO}| market for | APOS, U	1	kg	Industrial partner

Table 111: Inventory for unit process " 1 piece of WAAM cutting tool B5 " for Grade2XL demonstrator B-5 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of WAAM cutting tool B5	1	p	
Inputs from technosphere: materials/fuels			
WAAM cutting tool B5	81	kg	Industrial partner
USE WAAM cutting tool B5	81	kg	Industrial partner
EOL WAAM cutting tool B5	81	kg	Industrial partner

Table 112: Inventory for unit process " WAAM cutting tool B5" for Grade2XL demonstrator B-5 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM cutting tool B5	1	kg	
Inputs from technosphere: materials/fuels			
_Casting, bronze with one-use mould {GLO}| market for | APOS, U	1.41	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1.41	kg	Industrial partner
_Steel removed by milling, small parts {GLO}| market for | APOS, U	0.22	kg	Industrial partner
ALLUMAX plus, S.3	0.59	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	1.63	tkm	Industrial partner
WAAM equipment	2.92E-7	p	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	4.99	kWh	Industrial partner
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.41	kg	Industrial partner

Table 113: Inventory for unit process " EOL WAAM cutting tool B5" for Grade2XL demonstrator B-5 produced with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
EOL WAAM cutting tool B5	1	kg	
Outputs to technosphere: Waste treatment			
Casted AMPCO waste recycling	1	kg	Industrial partner

Demonstrator B6

Table 114: Inventory for unit process " 1 piece of forging die" for Grade2XL demonstrator B-6 repaired with conventional welding

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of forging die	1	p	
Inputs from technosphere: materials/fuels			
CM repair forging die	264	kg	Industrial partner

Table 115: Inventory for unit process '" CM repair forging die " for Grade2XL demonstrator B-6 repaired with conventional welding

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
CM repair forging die	1	kg	
Inputs from technosphere: materials/fuels			
Steel, low-alloyed {GLO}| market for | APOS, U	1	kg	Industrial partner
shielding gas ISO 14175 – M14 – ArCO - 5/2	0.81	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.2	tkm	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	21.9	kWh	Industrial partner
Emissions to air			
Particulates	0.0063	kg	(Dalquist, S., and Gutowski, T. 2004)
Carbon monoxide	0.00975	kg	(Dalquist, S., and Gutowski, T. 2004)
VOC, volatile organic compounds as C	9E-05	kg	(Dalquist, S., and Gutowski, T. 2004)
Outputs to technosphere: Waste treatment			
Scrap steel (waste treatment) {GLO}| market for scrap steel | APOS, U	0.6	kg	Industrial partner

Table 116: Inventory for unit process " shielding gas ISO 14175 – M14 – ArCO - 5/2 " for Grade2XL demonstrator B-6 repaired with conventional welding

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
shielding gas ISO 14175 – M14 – ArCO - 5/2	1	kg	
Inputs from technosphere: materials/fuels			
Oxygen, liquid {GLO}| market for | APOS, U	0.3	kg	Industrial partner
Argon, liquid {RER}| market for argon, liquid | APOS, U	0.92	kg	Industrial partner
Carbon dioxide, liquid {RER}| market for | APOS, U	0.5	kg	Industrial partner

Table 117: Inventory for unit process " 1 piece of forging die - WAAM" for Grade2XL demonstrator B-6 repaired with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
1 piece of forging die - WAAM	1	p	
Inputs from technosphere: materials/fuels			
WAAM repair forging die	48	kg	Industrial partner

Table 118: Inventory for unit process " WAAM repair forging die " for Grade2XL demonstrator B-6 repaired with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
WAAM repair forging die	1	kg	
Inputs from technosphere: materials/fuels			
Steel, chromium steel 18/8 {GLO}| market for | APOS, U	1	kg	Industrial partner
Wire drawing, steel {GLO}| market for | APOS, U	1.34	kg	Industrial partner
FERROMAX plus	1.68	kg	Industrial partner
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | APOS, U	0.88	tkm	Industrial partner
WAAM equipment	2.92E-7	p	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	19	kWh	Industrial partner
Emissions to air			
Particulates	0.0063	kg	(Dalquist, S., and Gutowski, T. 2004)
Carbon monoxide	0.00975	kg	(Dalquist, S., and Gutowski, T. 2004)
VOC, volatile organic compounds as C	9E-05	kg	(Dalquist, S., and Gutowski, T. 2004)
Outputs to technosphere: Waste treatment			
Scrap steel {GLO}| market for | APOS, U	2.18	kg	Industrial partner

Table 119: Inventory for unit process " Scrap metal waste recycling " for Grade2XL demonstrator B-6 repaired with wire arc additive manufacturing (WAAM)

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
Scrap metal waste recycling	1	kg	
Outputs to technosphere: Avoided products			
Steel, chromium steel 18/8 {GLO}| market for | APOS, U	1	kg	Industrial partner
Inputs from technosphere: electricity/heat			
Electricity, medium voltage {RER}| market group for | APOS, U	3.67	kWh	(Yellishetty, M., Mudd, G. M., Ranjith, P. G., and Tharumarajah, A. 2011)

Shielding gases

Table 120: Inventory for unit process " ALLUMAX plus " for Grade2XL demonstrators

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
ALLUMAX plus	1	kg	
Inputs from technosphere: materials/fuels			
Argon, liquid {RER}| market for argon, liquid | APOS, U	0.7	kg	Industrial partner
Helium {GLO}| market for | APOS, U	0.3	kg	Industrial partner

Table 121: Inventory for unit process " FERROMAX plus" for Grade2XL demonstrators

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
FERROMAX plus	1	kg	
Inputs from technosphere: materials/fuels			
Argon, liquid {RER}| market for argon, liquid | APOS, U	0.12	kg	Industrial partner
Helium {GLO}| market for | APOS, U	0.2	kg	Industrial partner
Carbon dioxide, liquid {RER}| market for | APOS, U	0.68	kg	Industrial partner

Table 122: Inventory for unit process " INNOMAX plus" for Grade2XL demonstrators

Flows and emissions	Value	Unit	Source
Outputs to technosphere: Products and co-products			
INNOMAX plus	1	kg	
Inputs from technosphere: materials/fuels			
Argon, liquid {RER}| market for argon, liquid | APOS, U	0.2	kg	Industrial partner
Helium {GLO}| market for | APOS, U	0.35	kg	Industrial partner
Carbon dioxide, liquid {RER}| market for | APOS, U	0.63	kg	Industrial partner