LASER BEAM MELTING FOR THE MANUFACTURING OF ROCKET ENGINE PARTS: A STUDY OF THE ENVIRONMENTAL IMPACTS

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Clean Space Industry, 18th october 2023

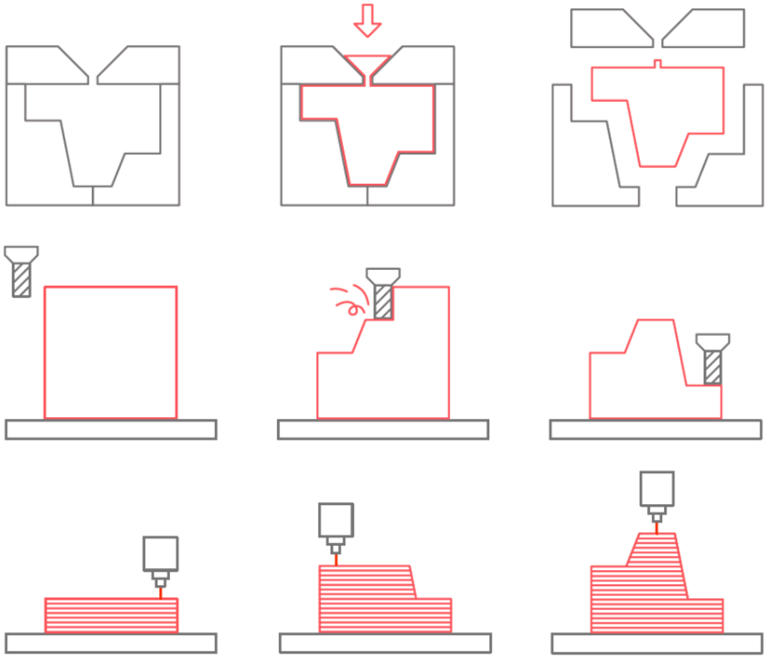
What is additive manufacturing ?

3 types of manufacturing :

FORMATIVE MANUFACTURING

SUBSTRATIVE MANUFACTURING

ADDITIVE MANUFACTURING



Formative manufacturing:

- Foundry
- Injection molding
- Forging
- Stamping...

Substrative manufacturing:

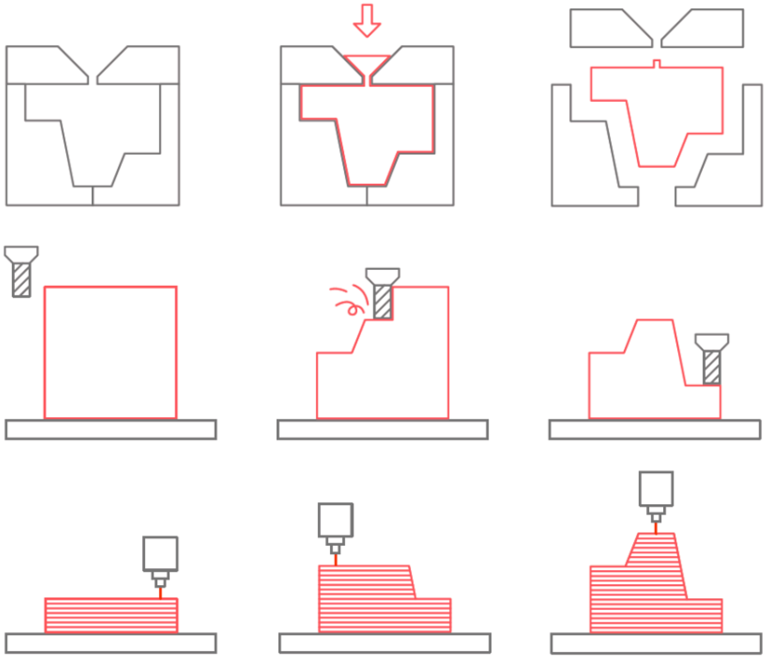
- CNC machining (milling, turning...)

Additive manufacturing:

- LPBF : Laser Powder Bed Fusion, LBM
- WAAM : Wire Arc Additive Manufacturing
- BMD : Bound Metal Deposition, FFF
- MBJ : Metal Binder Jetting...

What is additive manufacturing ?

3 types of manufacturing :



FORMATIVE MANUFACTURING

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SUBSTRATIVE MANUFACTURING

- CNC machining (milling, turning...)

ADDITIVE MANUFACTURING

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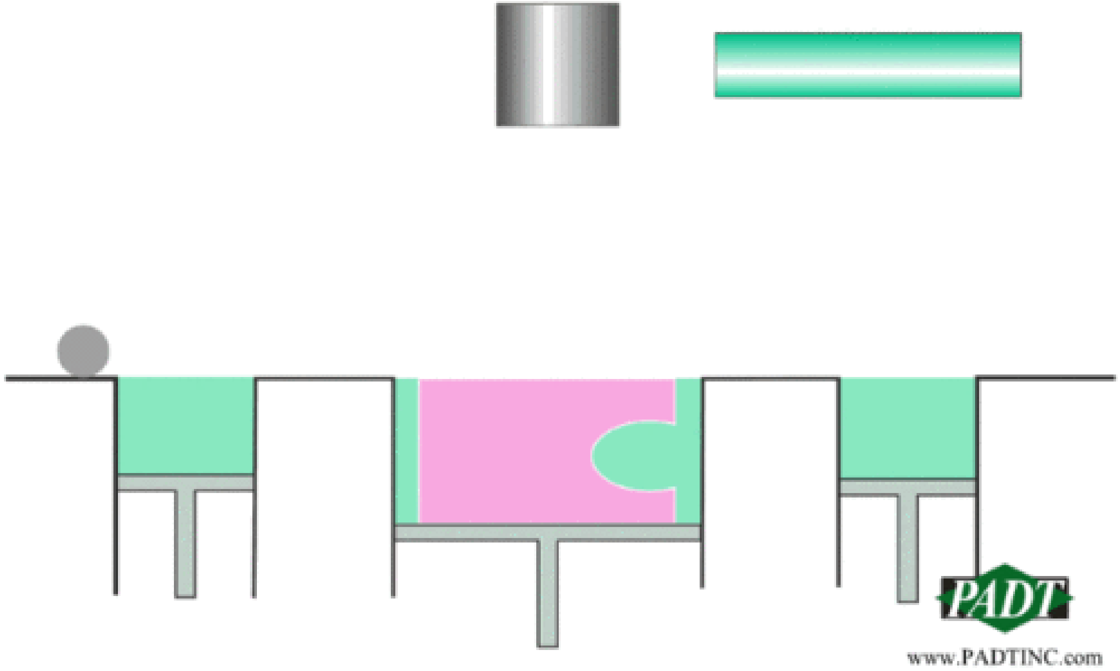
One of the most environmentally-friendly processes?

Laser Beam Melting (LBM, SLM, LPBF…)



Life Cycle Assessment (LCA)

One step of the eco-design process, NF EN 16524:

LCA

Step 0
Strategic analysis

- SWOT analysis

Step 1
Know the current situation

- Simplified environmental assessment with 35 questions
- Rating of the environmental aspects

Step2
Imagine and priorize the possible improvements

- 100 guideline proposals
- Simple rating system (economic, technical, strategic)

Step 3
Define the indicators to control the improvements

Step 4
Measure the improvements obtained

- Calculate the indicators after the redesign of the product

Step 5
Capitalize on and promote the work accomplished

- Evaluation of the approach
- Communication

How to conduct a LCA ?

1 Goal and scope definition
Definition of objectives, perimeter of study, functional unit

2 Life cycle inventory
Quantification of input and output flows at each stage of the life cycle

3 Impact assessment
Calculation of the environmental impacts

4 Interpretation

Validation of assumptions

Identification of the origin of the impacts

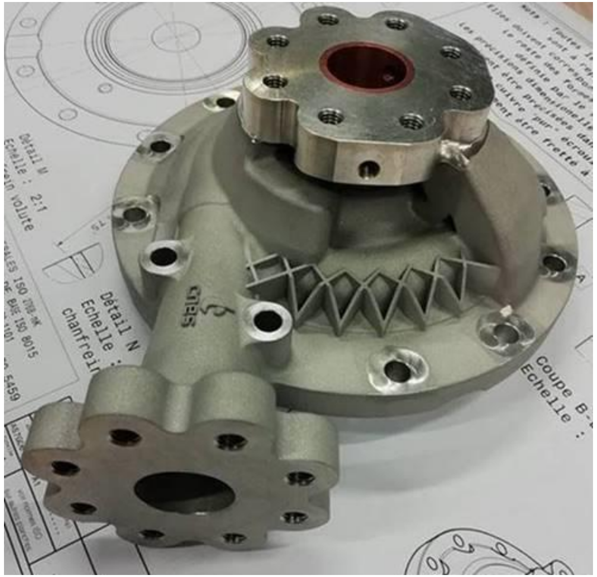
CETIM – CNES project content

1 Process Life Cycle Analysis : Laser bed fusion

Evaluation according to 5 indicators (including CO2 emissions) and for 4 distinct materials of the printing of 1kg of material

2 Product Life Cycle Analysis : pump volute casing

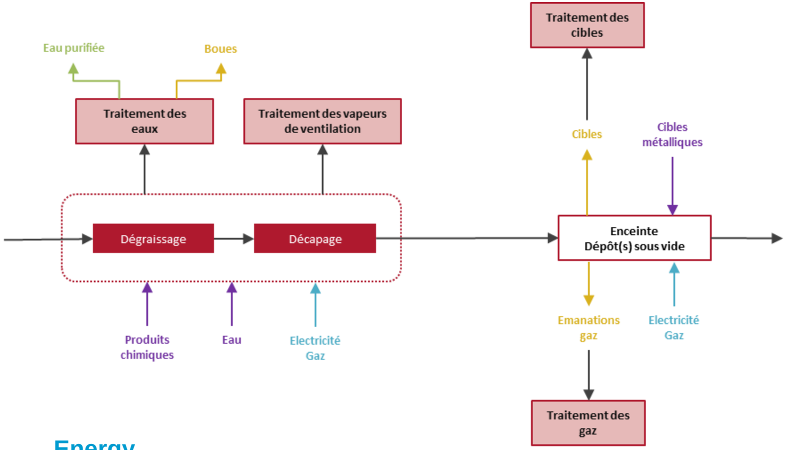
Comparative analysis, for aluminum and inconel, of an additive manufacturing with that of sand and lost wax casting



Studied part (CNES courtesy)

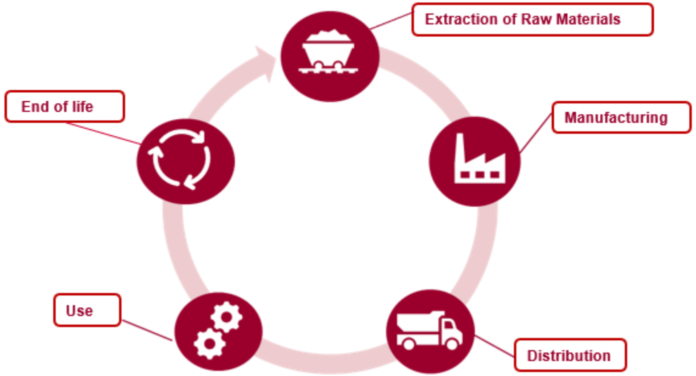
Product VS process approach

**Process approach → ** multi-stage approach throughout the *process synoptic*



Energy
Production supplies
Waste, emissions

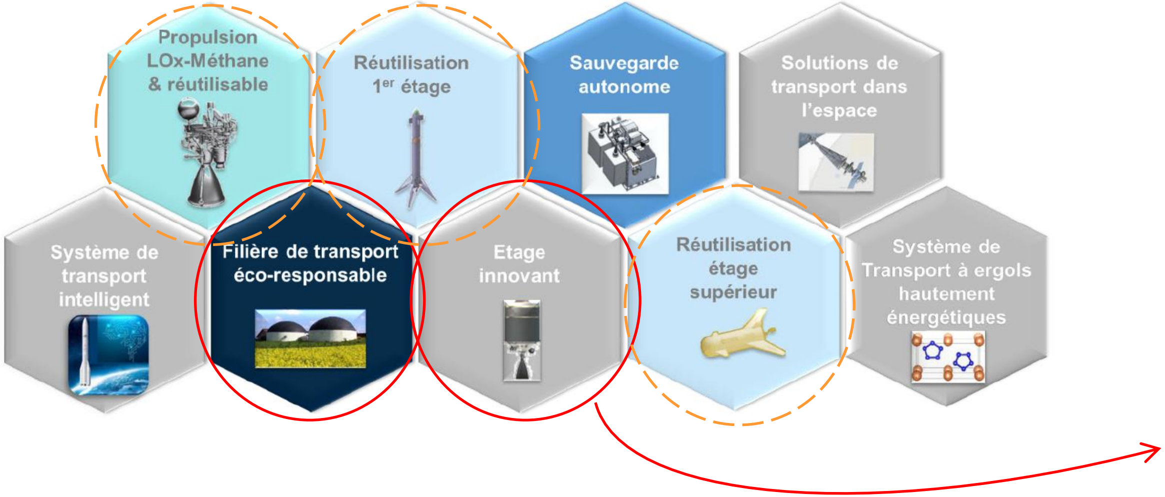
**Product approach → ** multi-stage approach throughout the *product life cycle*



CNES roadmap

Future launchers : stakes for system, technologies, methods and tools.

CNES organisation of activities* through PIV « priority innovation vectors »



See CNES technical roadmaps on: https://sciences-techniques.cnes.fr/fr/orientations-techniques

The topics of environmental studies and additive manufacturing fall into the following categories :

- Innovative solutions for propulsion and stage structural elements (1 main and 3 secondary PIV)
- Ecoresponsible space transportation (1 dedicated PIV)

* Research and Technologies, POC, demonstrations

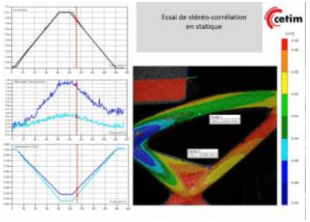
CETIM areas of expertise

Fatigue Optimisation Durability	Monitoring non-destructive testing & connected objects	Power transmission	Simulation	Sustainable Industrial performance	Assembly Technologies
Metallic materials and surfaces	Polymers and composite engineering	Fluid and sealing technologies	Metrology and calibration expertise	Integrated production systems	Advanced Additive Manufacturing

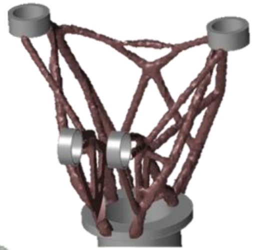
Strategic and technological intelligence	Failure analysis and expertise	Training and skills management	Software

1 Goal and scope definition
Definition of objectives, perimeter of study, functional unit

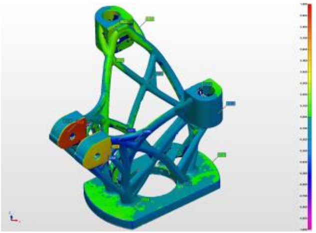
Tests



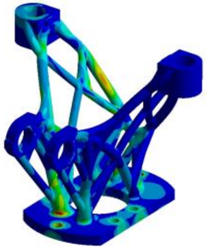
Design



Control



Simulation



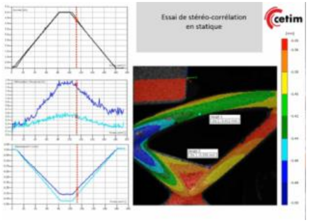
Manufacturing

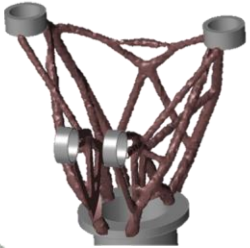
Finishing

Heat treatments

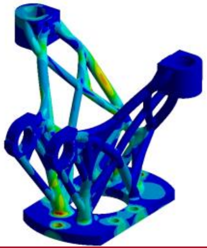
1 Goal and scope definition
Definition of objectives, perimeter of study, functional unit

Tests





Design



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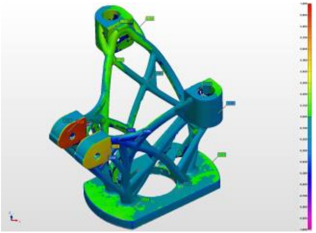
Control



Manufacturing

Finishing

Heat treatments

Cradle to factory gate

Indicators

- Climate change *(kg eq. CO_2)/(kg of manufactured part)*
- Human health *(DALY)/(kg of manufactured part)*
- Ecosystem quality *($PDF*m^2*yr$) /(kg of manufactured part)*
- Ressources depletion *(MJ)/(kg of manufactured part)*
- Water consumption *(eq m3) /(kg of manufactured part)*

1 **Goal and scope definition**
Definition of objectives, perimeter of study, functional unit

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Environmental impact sources

- Material consumption *kg of waste powder / kg of manufactured part*
- Fluid consumption - process gases *liters consumed / kg of manufactured part*
- Energy consumption *kWh / kg of manufactured part*
- Consumables and machines

Goal and scope definition (1)
Definition of objectives, perimeter of study, functional unit

Indicators

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Additional phases included in the database

Environmental impact sources

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Manufacturing cycle phases

1 Goal and scope definition
Definition of objectives, perimeter of study, functional unit

Indicators

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MODELING

	Material	Fluid	Energy	Consumables and machines
Additional phases included in the database	Extraction of ores Transport of the ores to the atomization site Transport of the powder to the machines	Argon gas supply Argon gas production Compressed air production	Electricity delivery Power generation	Manufacture of materials Manufacturing of the elements (shaping, assembly...)
Environmental impact sources	Material consumption *kg of waste powder / kg of manufactured part*	Fluid consumption - process gases *liters consumed / kg of manufactured part*	Energy consumption *kWh / kg of manufactured part*	Consumables and machines
Manufacturing cycle phases	Atomization of the powder FA process: Powder losses in the machine, during sieving, due to recycling tolerances, manufacturing waste (supports) Manufacturing failure rate	Atomization of the powder FA process : Consumption of argon and compressed air in the machine and related equipment Use of compressed air to depowder the parts	Digital chain: CAD, CAM, generation of the control file Atomization of the powder Cleanroom consumption FA process: Electrical supply of the LBM machine and related equipment (vacuum cleaners, sifters, machine standby, heating, preparation, construction...) Separation and machining of the build plates	Use of disposable (overshoes, gloves, coveralls, masks, wipes) and reusable protective equipment Use of machines and peripheral equipment Use of build plate Consumption of filters

1 Goal and scope definition
Definition of objectives, perimeter of study, functional unit

Indicators	Climate change *(kg eq. CO2)/(kg of manufactured part)*	Human health *(DALY)/(kg of manufactured part)*	Ecosystem quality *(PDF*m²*yr) /(kg of manufactured part)*	Ressources depletion *(MJ)/(kg of manufactured part)*	Water consumption *(eq m3) /(kg of manufactured part)*

MODELING ↑

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Legend:
Data not included in the study

cetim

2 **Life cycle inventory**
Quantification of input and output flows at each stage of the life cycle

FUNCTIONAL UNIT :

1kg =

of part

?
liters of argon gas

?
consumables

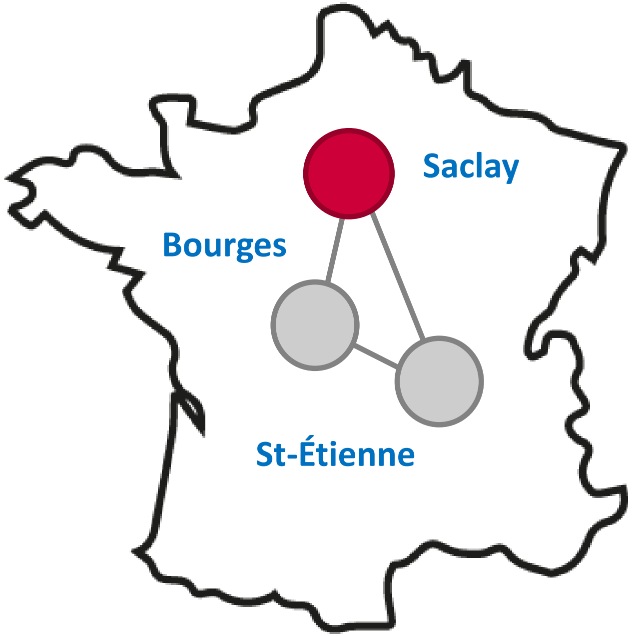
?
kWh

?
kg of lost powder

?
liters of compressed air

→ Internal data from various CETIM sites : from 283 fabrications between 2013 and 2022 from 3 sites and 10 different materials, machine instrumentation

2 Life cycle inventory
Quantification of input and output flows at each stage of the life cycle



Additive Factory Hub (AFH)

- 3DS ProX DMP320 (build volume 275 x 275 x 420mm)
- AddUp FORMUP 350 (build volume 350 x 350 x 350mm)

→ Supplier data

→ Literature data

During the print :

2 **Life cycle inventory**
Quantification of input and output flows at each stage of the life cycle

FUNCTIONAL UNIT :

1kg =
of part

20,68
kWh

5218,9
liters of argon gas

1,38kg
of lost powder

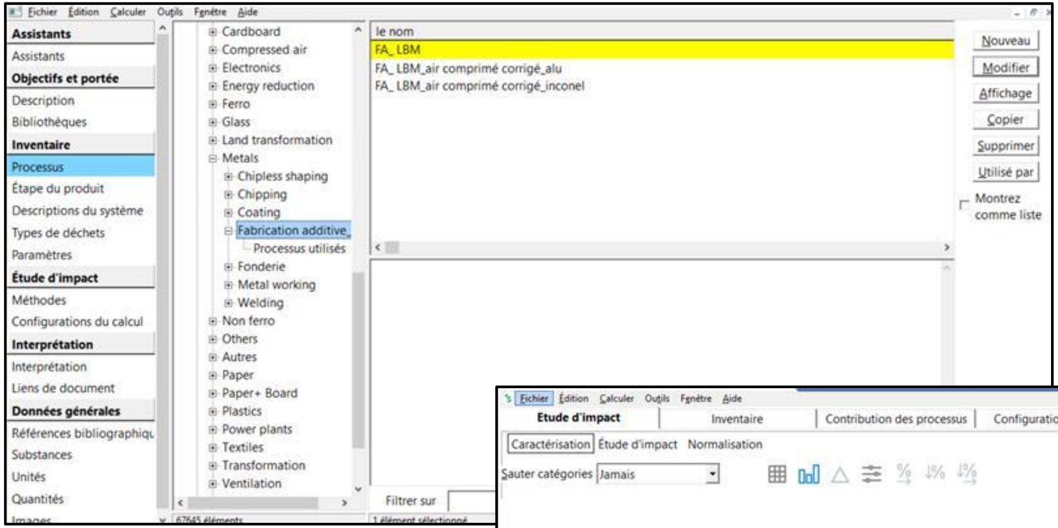
2713,8
liters of compressed air

+
consumables

3 **Impact assessment**
Calculation of the environmental impacts

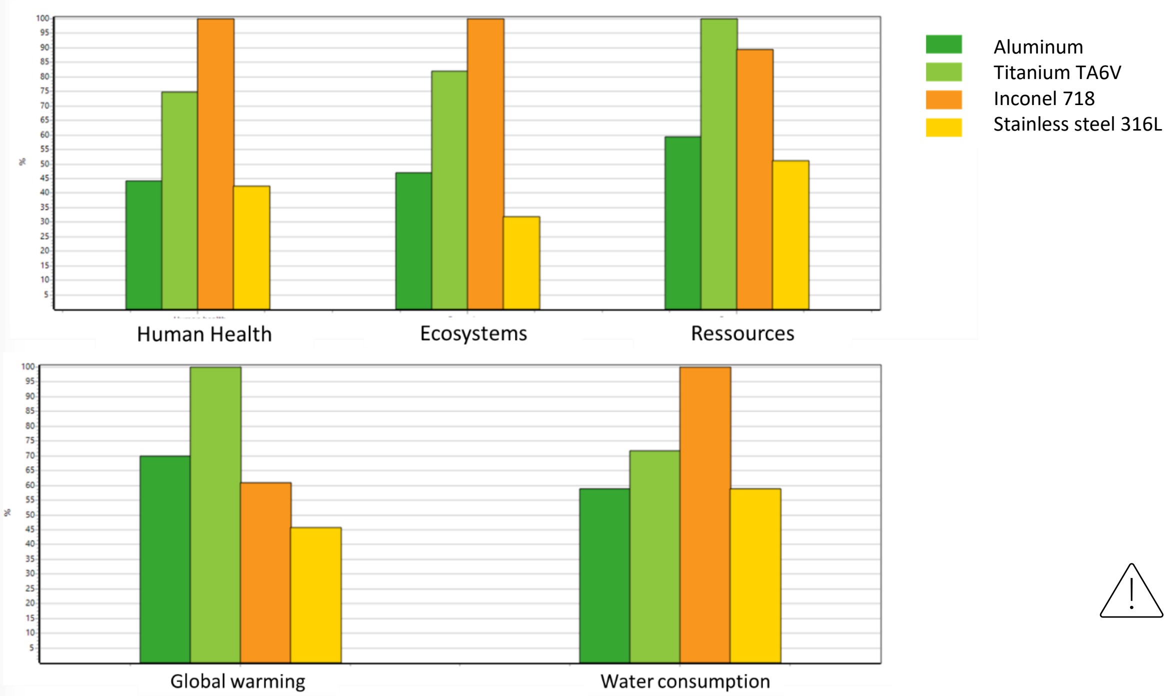
SimaPro

ecoinvent



Characterization method « ReCiPe 2016 Endpoint (E) V1.06 » in the EcoInvent 3 database, cut-off with the Simapro software 9.3.0.3

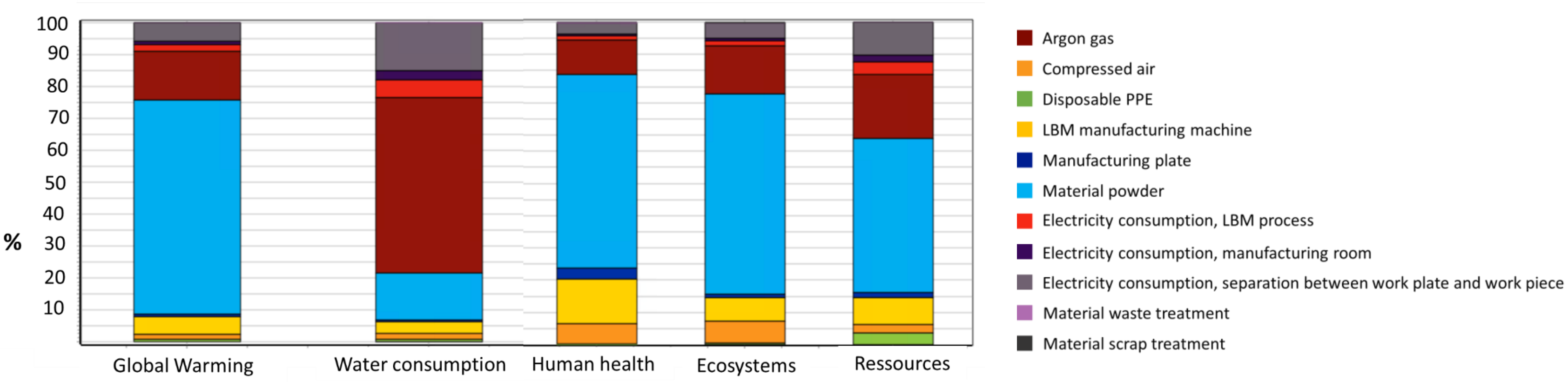
Comparaison between materials for a same mass produced



Producing a part in titanium or inconel is more impactful than producing a part in aluminum or stainless steel with the same mass.

Not representative of a product, manufactured for a defined volume and not for a specific weight.

Main impact contributors of the LBM process



Bilan environnemental du procédé LPBF - aluminium

All materials considered, the main contributors to the impact of additive manufacturing are the **argon gas** and the **powder used**.

CASTING

ADDITIVE MANUFACTURING

LPBF

Use of previously created process LCA data

Topological optimization
Weight aluminum : 0,75kg
Weight inconel : 2,24kg

Aluminum : Sand Casting

Simplified process LCA

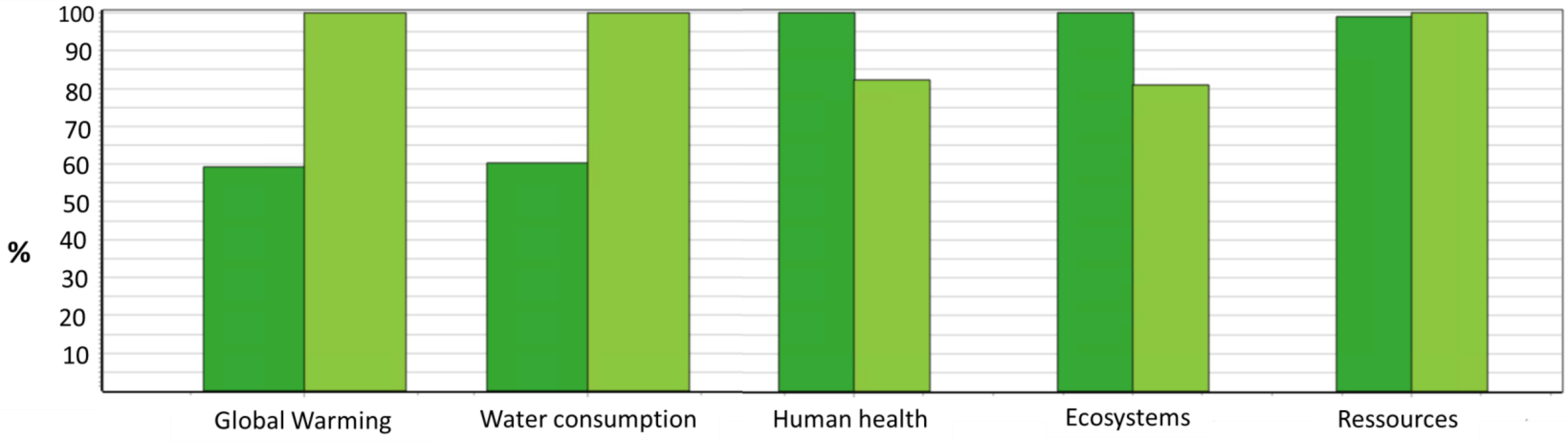
Weight aluminum : 0,874kg

Inconel : Lost-wax casting

Use of environmental data already in the database

Weight inconel : 2,66kg

Comparison between processes (aluminum)



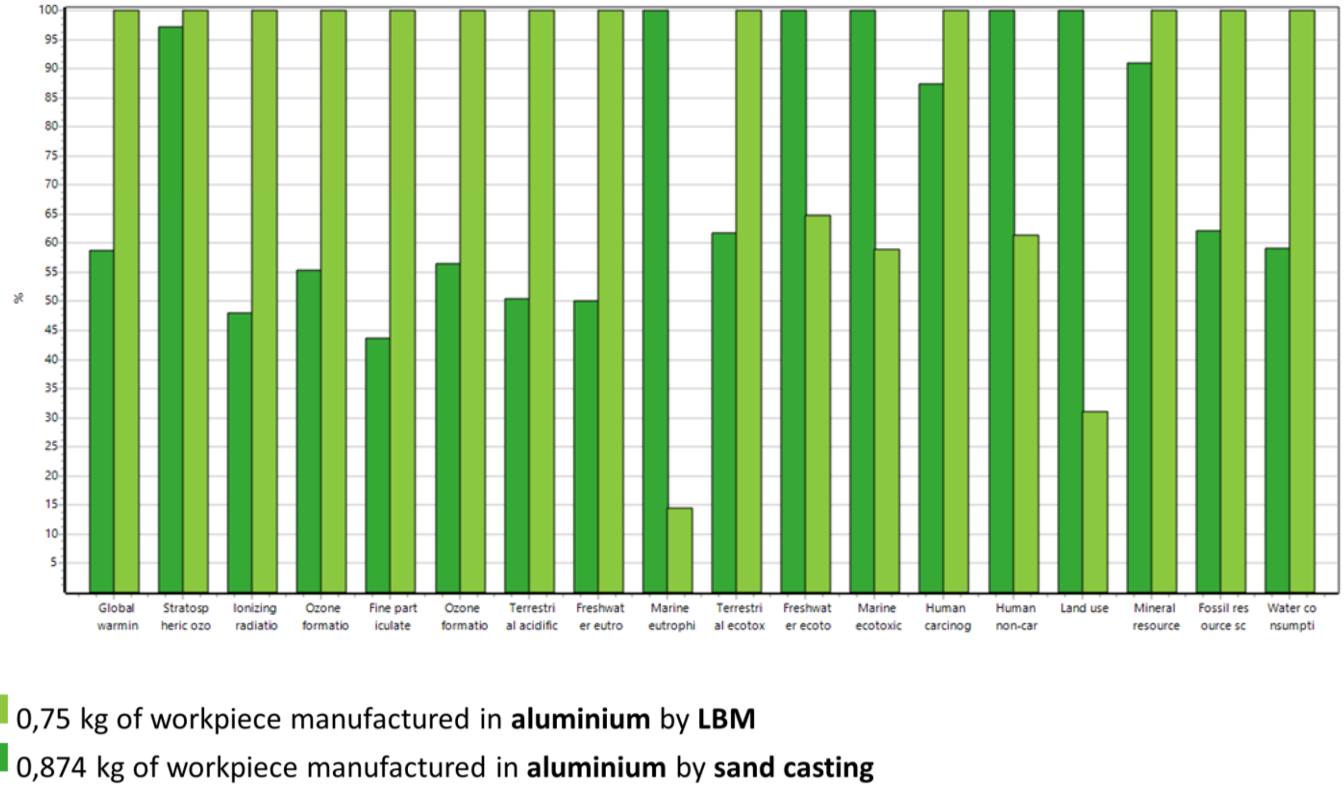
0,75 kg of workpiece manufactured in **aluminium** by **LBM**

0,874 kg of workpiece manufactured in **aluminium** by **sand casting**

Midpoint indicators: the impact of manufacturing a turbopump volute using the LBM process is around 40% greater than that of sand casting.

Endpoint indicators: impact difference of around 20% in favor of the LBM process

Comparison between processes (aluminum)



→ Similar results for inconel, difference in impact between LPBF and sand casting nuanced

4 **Interpretation**

Validation of assumptions

Identification of the origin of the impacts

- LBM metal additive manufacturing is often considered to be one of the most environmentally friendly processes → Assumption mitigated by this study

- For an equal mass, the manufacturing by LBM in aluminum or stainless steel is less impactful than in titanium or Inconel
- For all materials considered, the main contributors to the impact of LBM process are the argon gas and the powder used.

- When applied to a product LCA, no generalization can be made about the relative environmental impact of the LBM process with regards to that of casting

4 **Interpretation**

Validation of assumptions

Identification of the origin of the impacts

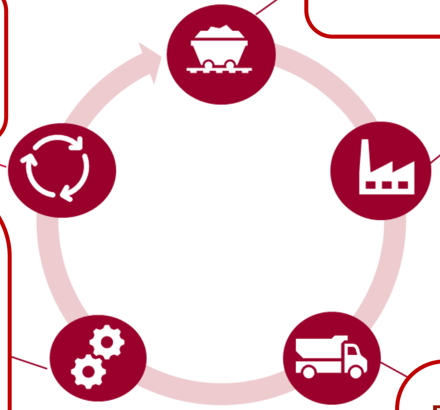
- Discussion and outlooks:
  - Important number of R&D machines
  - Disparities in data reliability between the explored processes
  - Topics of powder manufacturing by atomization, powder ageing and waste treatment to be explored in greater depth
  - Parameters that can potentially influence environmental impact: part type, production size, etc.

Environmental gains of additive manufacturing

Study on the entire part life cycle, « cradle to grave »

Extraction of raw materials ✓

End of life



Manufacturing

- Design
- Simulation
- Printing ✓
- Heat treatments
- Finishing
- Control, Tests

Use

Distribution

Environmental gains of additive manufacturing

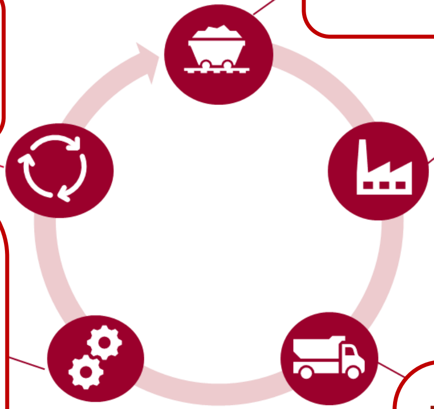
Study on the entire part life cycle, « cradle to grave »

Extraction of raw materials

Recycling of unfused powder (LMB)

End of life

Repair of parts (deposit welding…)



Manufacturing

Lightening of components via topological optimization or lattice structures: reduction in the amount of material used

Elimination of the need for tooling and molds

Use

Lightening of components via topological optimization or lattice structures → reduced weight of transport-related products and associated fuel consumption

Redesign of fluid veins: diminution of pressure drops phenomenon

Optimized thermal efficiency: internal channels, conformal cooling

Distribution

Reduced carbon footprint linked to transport through relocation as close as possible to the customer

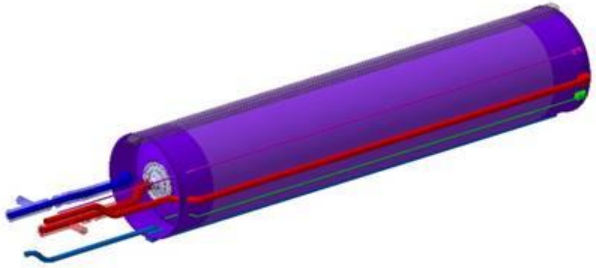
On-demand manufacturing: reduction of losses linked to the anticipation of spare parts

→ Metal additive manufacturing for a sustainable industry

Future CETIM - CNES project

Project 1: Creation of environmental data for the WAAM process → **Phase 1** Framing → **Phase 2** Data collection → **Phase 3** WAAM environmental data

Project 2: eco-design approach Callisto tank → **Phase 1** Framing → **Phase 2** Environmental diagnosis of reference product → **Phase 3** Concept generation → **Phase 4** Evaluation of eco-designed product → **Phase 5** Review



Going for the future

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