Environmental and economic process comparison

Strumenti dell'Ingegneria per l'Industria 4.0

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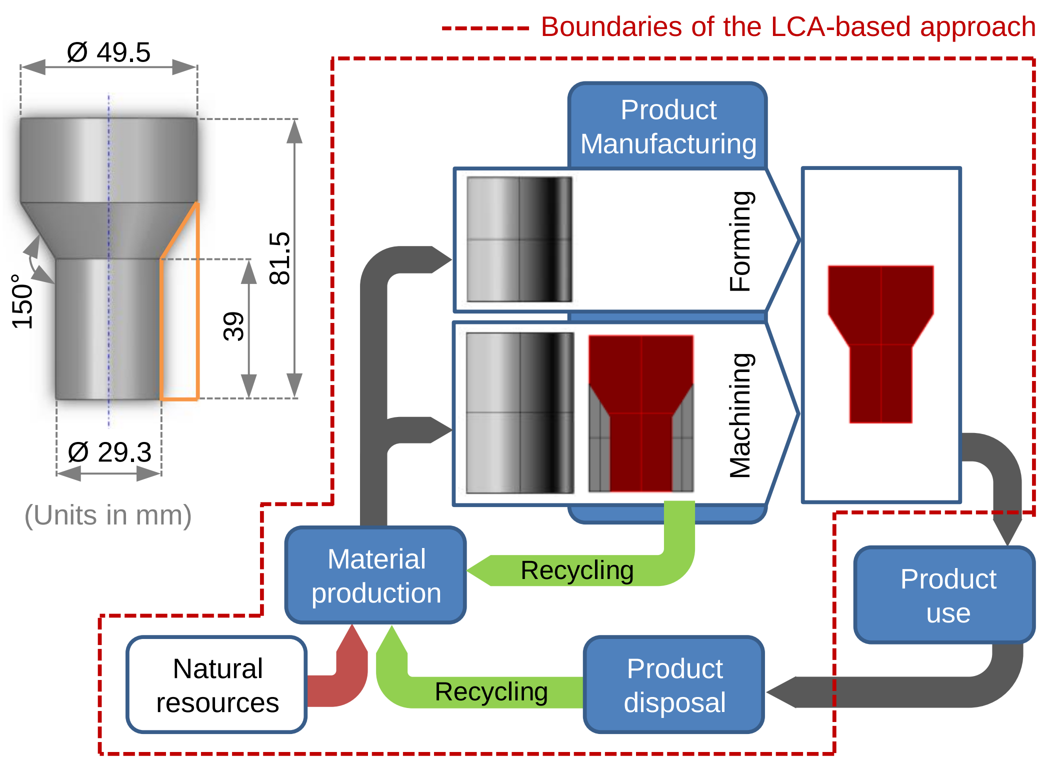
Target

- The industrial world is facing the challenge of reducing emissions by means of energy- and resource-efficient manufacturing strategies.
- In some cases, the exerted emissions and the energy demands related to conventional manufacturing processes are not as intensive as those required to extract and produce the raw materials of which the workpieces are made.
- Therefore, the consciousness of the impact of material usage and the eco-informed choice of the end-of-life scenarios are both needed in view of sustainable development.

- **Comparison of environmental impact of forming and machining processes, for the production of Al-based components, when varying the aluminum recycling strategy.**

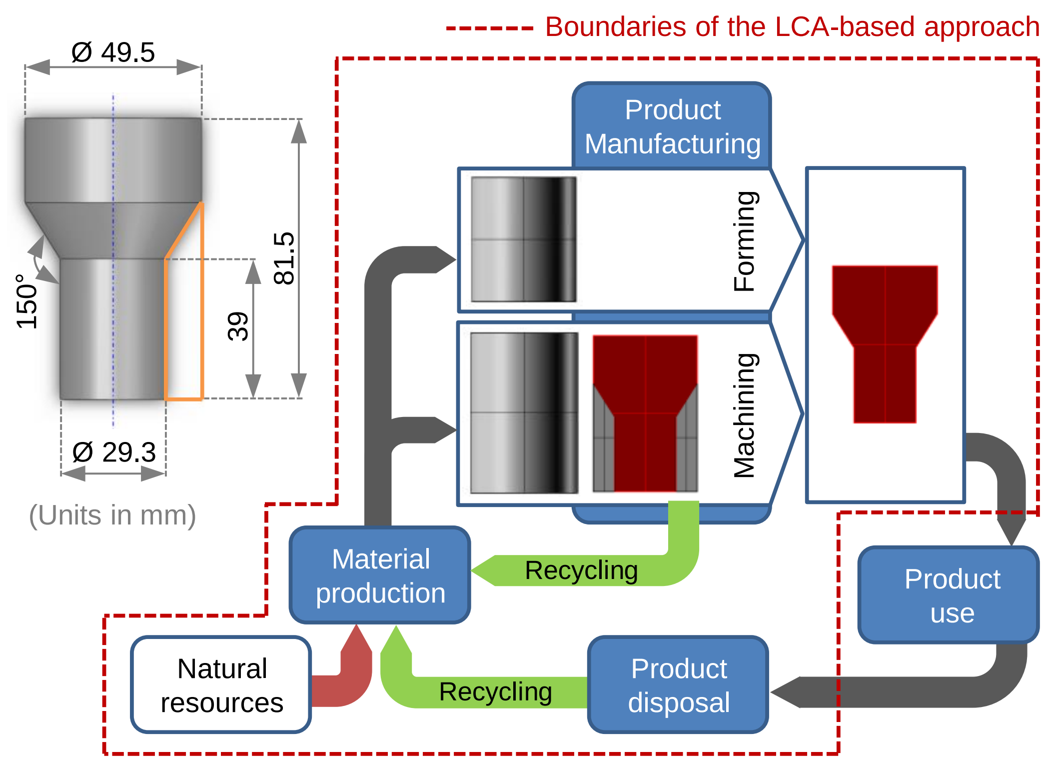
Methodology

- Methodology for comparing the environmental impact of forming and machining processes.
- Production of an axy-symmetric shaped component made of an AA-7075 T6 aluminum alloy.
- A single-step hot extrusion (*bulk forming*) process and a machining (*turning*) process were compared.
- Often, the process choice is driven by cost or production rate requirements.
- <u>The present research aims at including also environmental-related indicators in the decision step.</u>



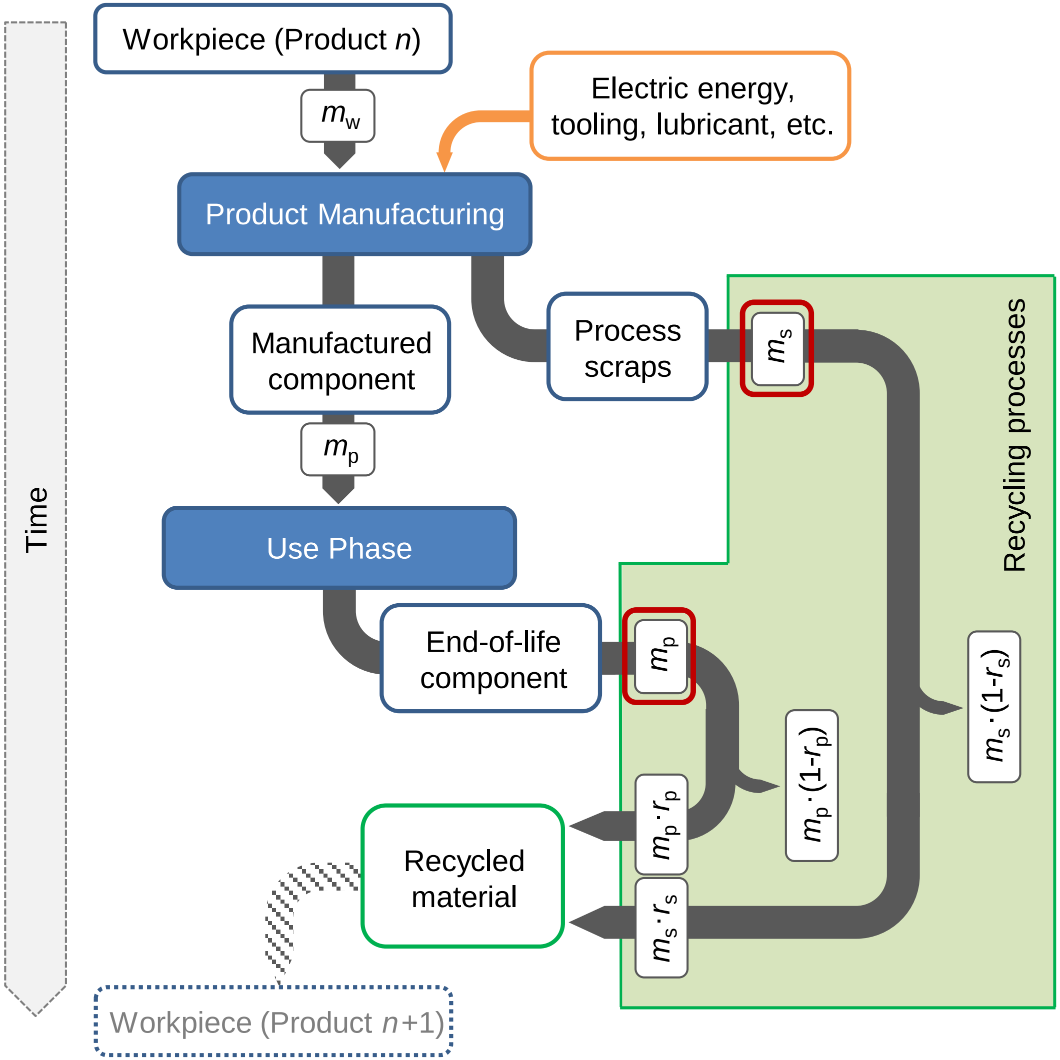
Methodology

- The single component production (within a defined batch size) was assumed as a basis for processes comparison.
- The energy flows and the CO_2 emissions were considered.
- Former results proved that workpiece material usage has a significant effect on the environmental impact, even varying factors of influence as production batch size and part geometry.
- Thus, <u>the impact assessment of the aluminum recycling strategy is of primary importance.</u>



Material production and recycling benefit awarding

- For a system in which different kinds of material scraps are produced at different life-cycle stages, all the various contributions to the material recycling have to be added.
- The component (weighing m_p) is produced from a workpiece (m_w) via forming or machining.
- The process scraps as well as the component (which is disposed at the end of its first life) are assumed to be both recycled.



Material production and recycling benefit awarding

- The amount of material effectively recycled from both process scraps ($m_s \cdot r_s$) and bulk material ($m_p \cdot r_p$) will contribute to produce another workpiece.
- According to the substitution method (that gives a credit for future *recyclability*) :

$$E_M = H_V \cdot m_w + \boxed{-r_p \cdot \left(H_V - H_{R,p}\right) \cdot m_p + -r_s \cdot \left(H_V - H_{R,s}\right) \cdot m_s} \quad (MJ)$$

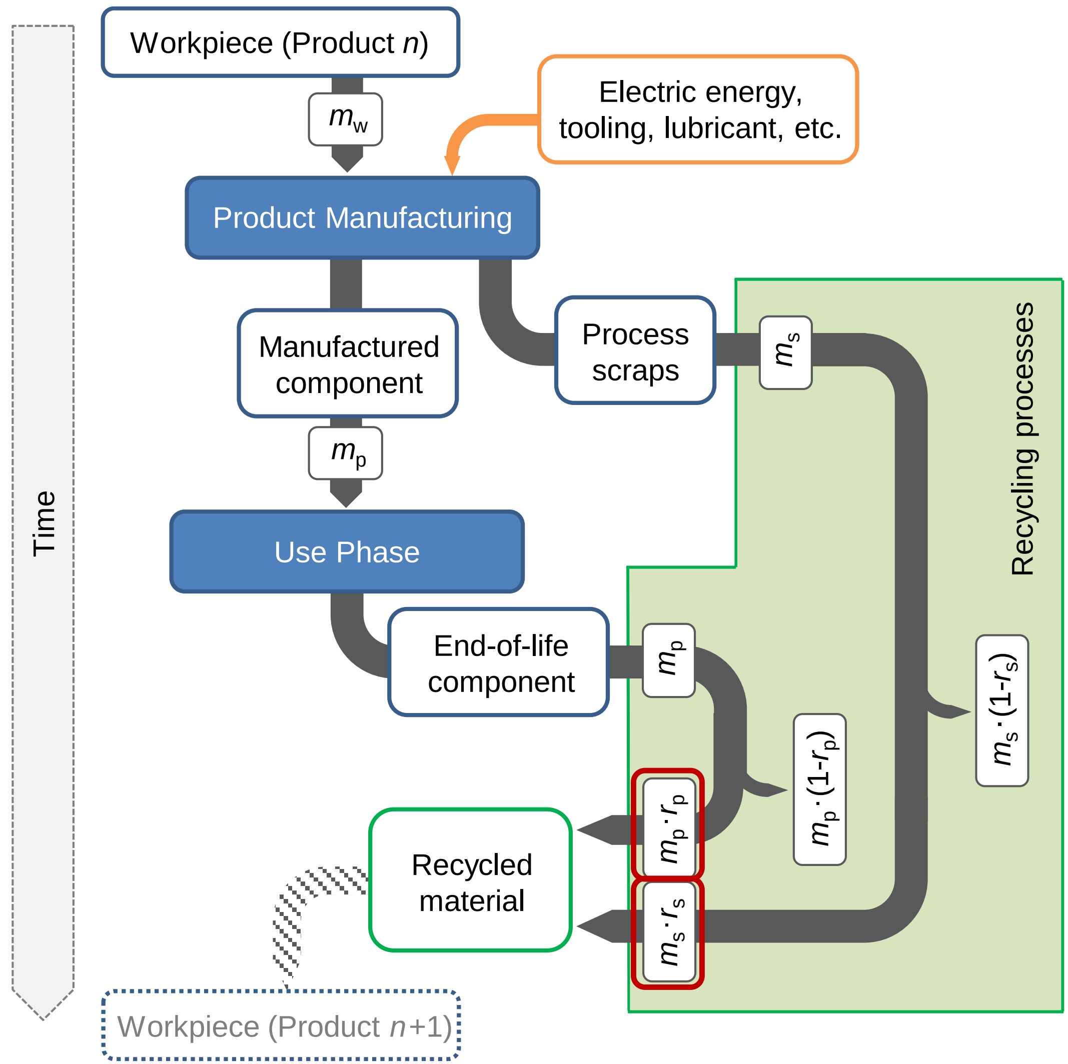
where:

H_V Embodied energy for primary production

$H_{R,p}$ Embodied energy for bulk recycling

$H_{R,s}$ Embodied energy for process scrap recycling

r Recyclability



Aluminum recycling processes

- Secondary aluminum production from scrap by *traditional remelting* requires much less energy than primary production.
- Despite that, the aluminum recycling process is still an energy-intensive one, and the overall energy efficiency is very low.

Traditional remelting

- Permanent material losses occur during remelting, because of *oxidation*.
- This aspect is particularly relevant for chips: light-gauge scraps, having a high surface area-to-volume ratio, tend to float on the surface of the melt, causing a significant oxidation that can be as high as 15-20%.

Eco-property		Symbol (UM)	Value
Primary production	Embodied energy	H_V (MJ/kg)	**202.0**
	CO_2 footprint	$CO_{2\,V}$ (kg/kg)	**12.7**
Conventional recycling (CR), i.e. remelting	Embodied energy	H_R^{CR} (MJ/kg)	**34.3**
	CO_2 footprint	$CO_{2\,R}^{CR}$ (kg/kg)	**2.7**
	Recyclability (bulk)	r_p^{CR}	**0.95**
	Recyclability (chips)	r_s^{CR}	**0.85**
Solid bonding recycling (SB)	Embodied energy	H_R^{SB} (MJ/kg)	**7.3**
	CO_2 footprint	$CO_{2\,R}^{SB}$ (kg/kg)	**0.87**
	Recyclability (chips)	r_s^{SB}	**1.00**

Aluminum recycling processes

- Recently, various *solid state recycling approaches* have been developed.
- The use of hot extrusion as recycling method is so far the most analyzed one.
- This envisages turning chips directly into fully dense profiles by a cold compacting step followed by a hot extrusion one.

Haase et al. (2012) Materials Science and Engineering A 539: 194-204

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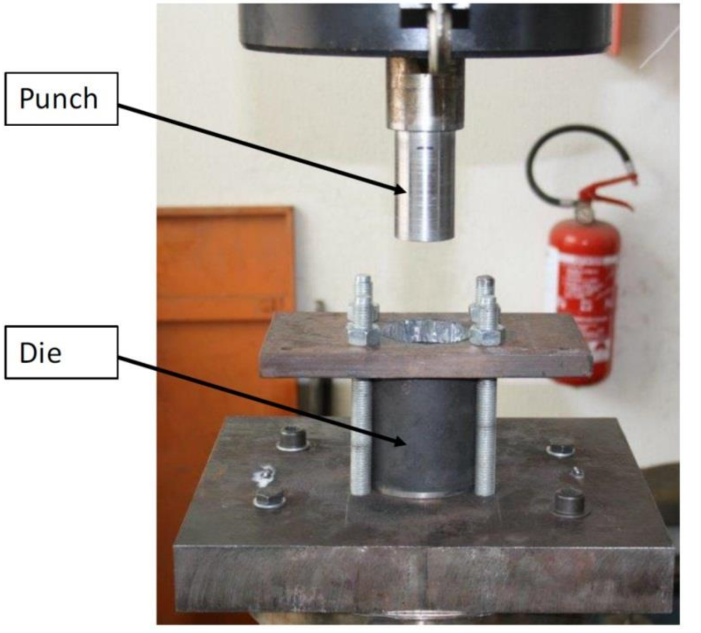
Manufacturing

- The energy demand for manufacturing has been experimentally assessed.
- When *machining*, turning tests were performed on a Cortini F120/25 CNC lathe.
- When *forming*, a four pillars electro-hydraulic Instron 1276 machine with a load capability of 1000 kN was used.
- The electric energy demand for processing was measured with respect to productive and non-productive operational modes.
- In addition, the energy footprint for tooling was considered for both the processes.
- CO_2 emissions where assessed either directly, or via the Carbon Emission Signature (CES) method.



Energy for manufacturing: machining

- *Energy demand for manufacturing in machining* ($E_{MFG}{}^{m}$):

$$E_{MFG}{}^{m} = \frac{E_{MT}{}^{m}}{\eta} + E_{tooling}{}^{m} =$$

$$= \frac{\left(E_C + E_{NC}\right)}{\eta} + E_{tooling}{}^{m} \qquad \left(\frac{MJ}{part}\right)$$

- The contributions of both cutting (E_C) and non-cutting (E_{NC}) operations are included in the assessment of the electric energy consumption of the machine tool ($E_{MT}{}^{m}$).
- The energy conversion coefficient η was introduced in order to account for the energy losses occurring at the various steps of the production of electricity from primary energy sources.
- In addition, the cutting tool footprint ($E_{tooling}{}^{m}$) is considered.

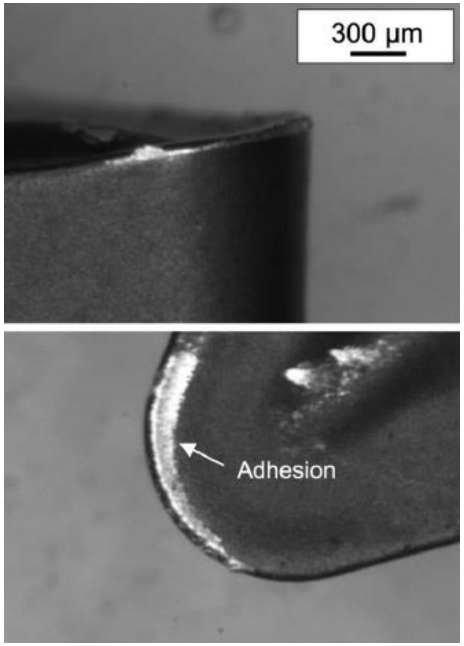
Energy for manufacturing: machining

- *Cutting tool footprint*:

$$E_{tooling}{}^{m} = \sum_{i=1}^{n} \left(\frac{E_{ct}}{n_e} \cdot \frac{t_c}{T_L} \right)_i =$$

$$= \left(\frac{E_{ct}}{n_e} \cdot \frac{t_c}{T_L} \right)_{roughing} + \left(\frac{E_{ct}}{n_e} \cdot \frac{t_c}{T_L} \right)_{finishing} \qquad \left(\frac{MJ}{part} \right)$$

- The footprint of each *i*-th cutting tool applied in the manufacturing route (i.e. for roughing or finishing operations) has been included.
- The ratio between the embodied energy of the cutting tool (E_{ct}, in MJ/insert) and the number of cutting edges (n_e) was multiplied by the ratio between the cutting time (t_c, in min) and the tool life (T_L, in min).
- *The energy used to produce a cutting tool is spread over each manufactured component, on the basis of the tool consumption ratio.*



Energy for manufacturing: forming

- *Energy demand for manufacturing when forming ($E_{MFG}{}^{f}$):*

$$E_{MFG}{}^{f} = \frac{E_{MT}{}^{f}}{\eta} + E_{heating} + \frac{E_{tooling}{}^{f}}{N} =$$

$$= \frac{\left(E_P + E_{NP}\right)}{\eta} + E_{heating} + \frac{E_{tooling}{}^{f}}{N} \qquad \left(\frac{MJ}{part}\right)$$

- The energy to manufacture each part ($E_{MFG}{}^{f}$, in MJ/part) comprises the electric energy due to the machine tool demand ($E_{MT}{}^{f}$), including both productive and non-productive times
- The energy for heating the billet ($E_{heating}$), as well as the energy for tooling ($E_{tooling}{}^{f}$) have been included.
- The impact of tooling was assessed by considering the embodied energy of the AISI H13 used for both punch and die, and the energy the manufacturing operations. The total energy demand has been divided by the produced batch size (N).

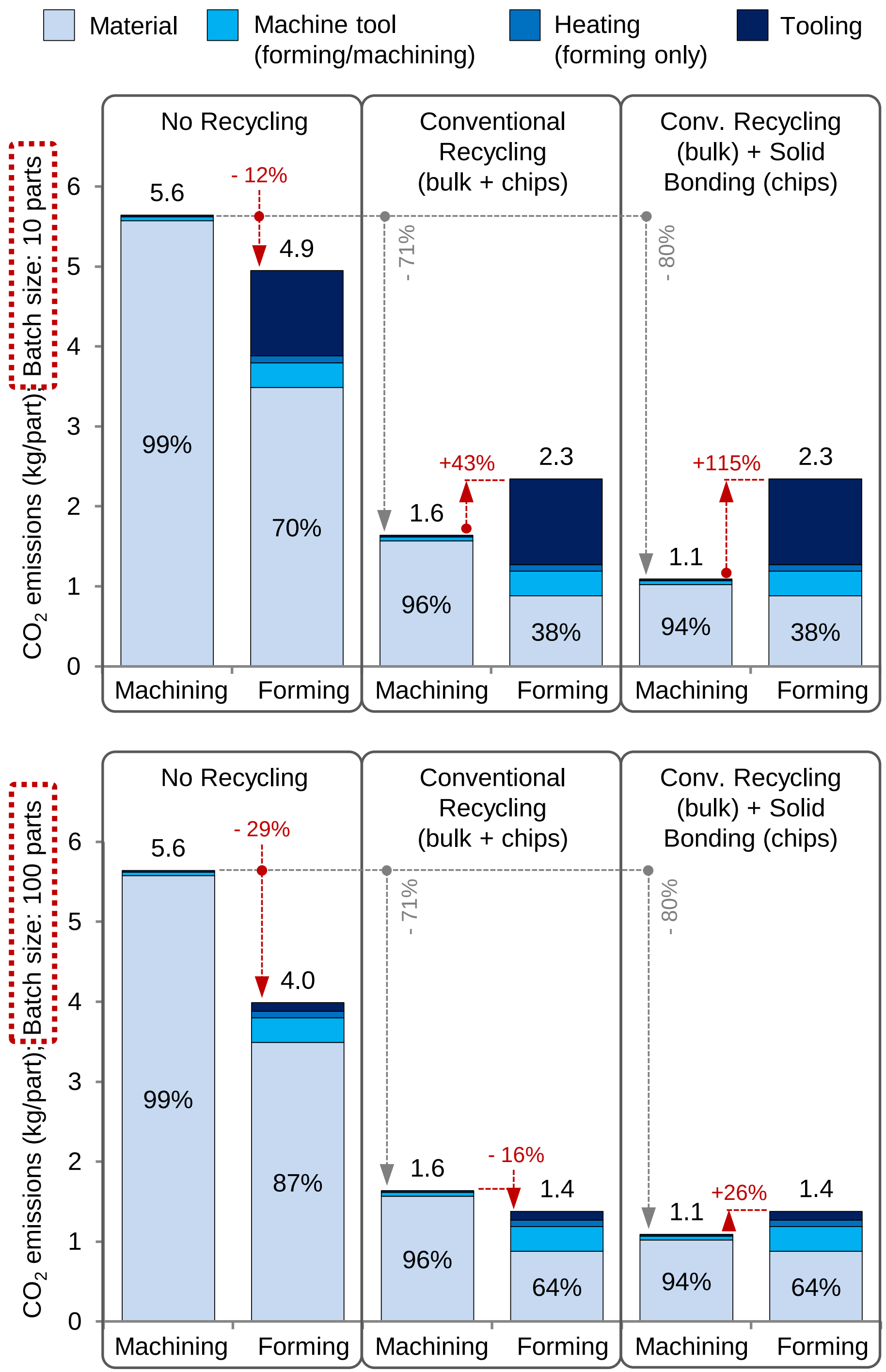
Results and discussion

- In order to analyze the influence of the recycling process, different scenarios have been hypothesized:

    (1) credit from recycling not considered;

    (2) conventional recycling approach for both part material (bulk) and process scraps (chips);

    (3) conventional recycling approach for part material (bulk) coupled with the solid bonding recycling approach for the machined chips.

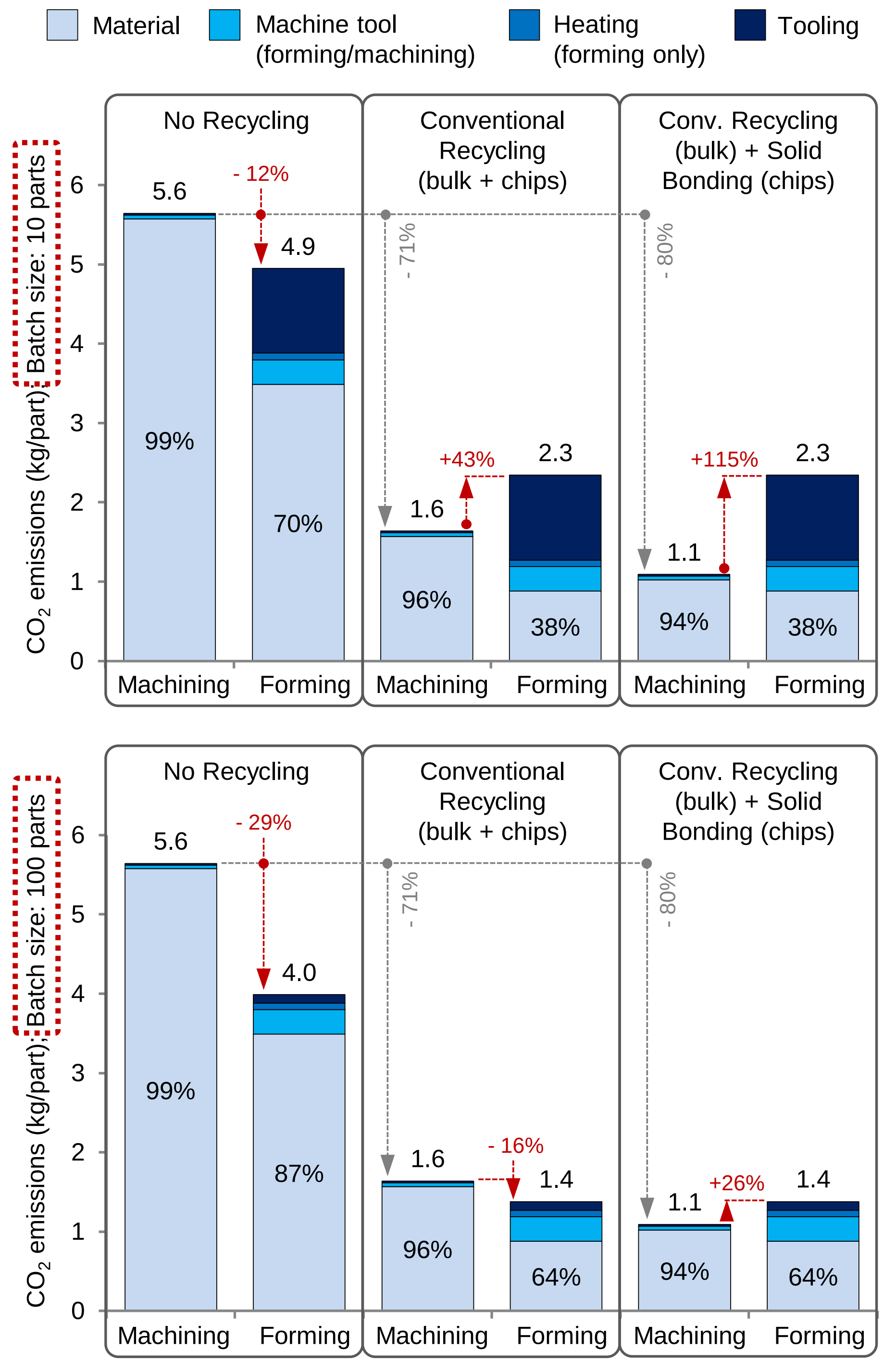


CO_2 emissions arising from the production of a part belonging to a batch size equal to 10 and 100.

For each scenario, the impact of each factor of influence is detailed.

Results and discussion

- The impact related to material production is usually dominant (particularly for machining).
- Recycling (in general) leads to substantial energy and CO_2 emissions savings.
- Moreover, solid state recycling enables relevant environmental impact benefits to be obtained, and it even causes the overturn of processes comparison results, despite of the considered batch size.

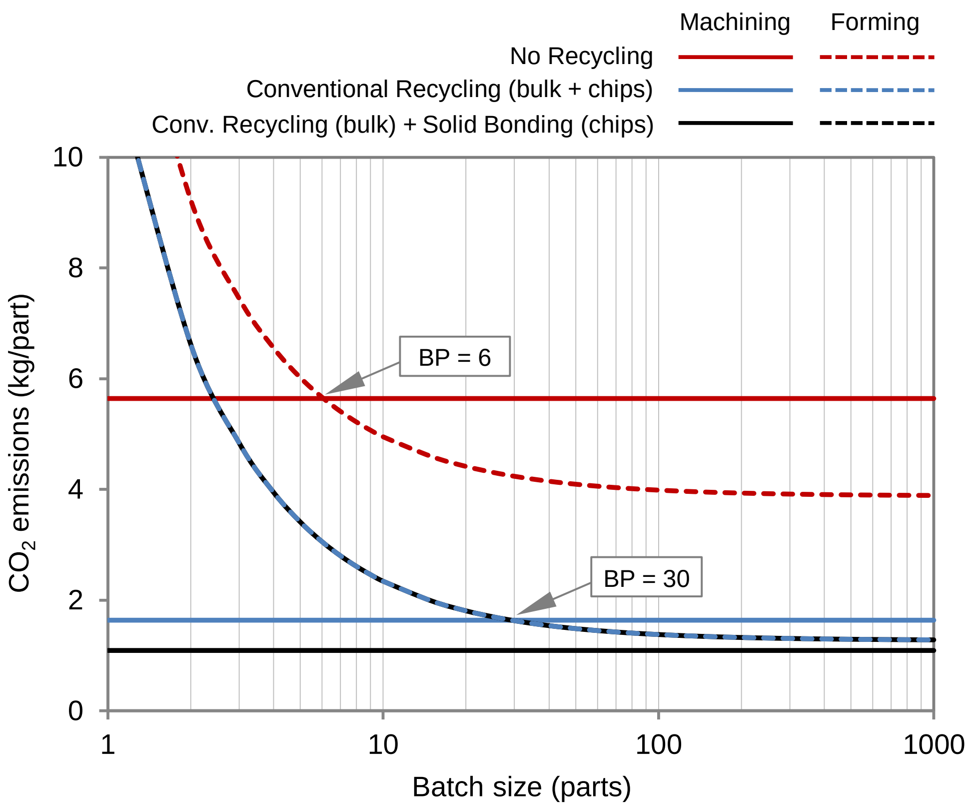


CO_2 emissions arising from the production of a part belonging to a batch size equal to 10 and 100.

For each scenario, the impact of each factor of influence is detailed.

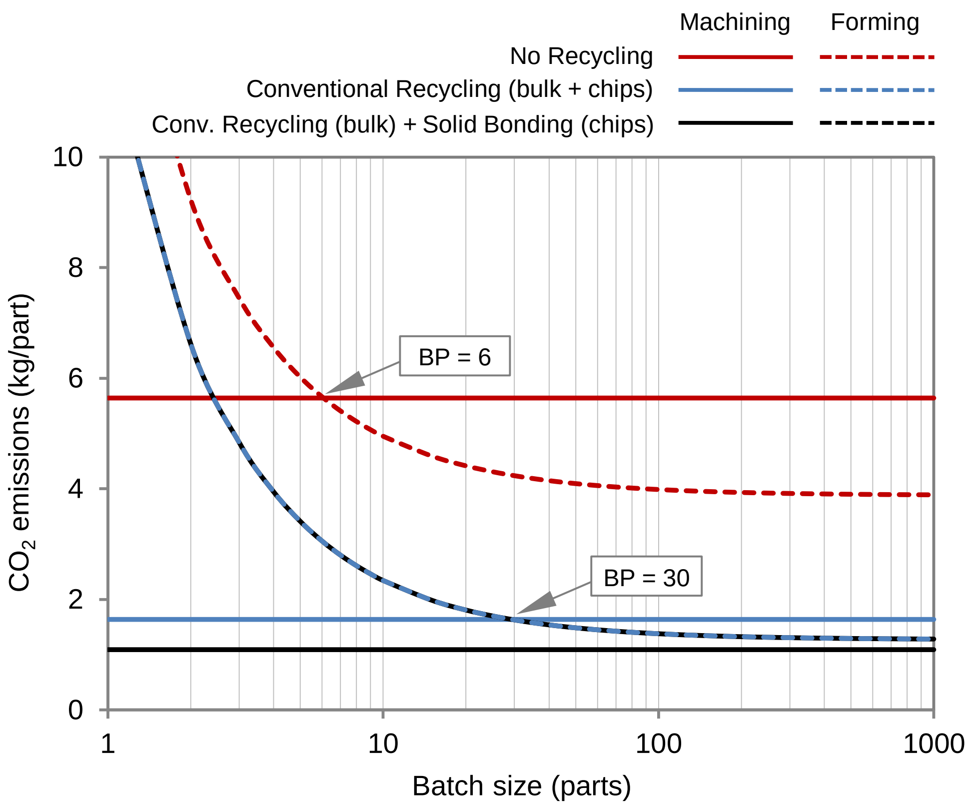
Results and discussion

- For high production volumes, the forming approach is generally the greener one.
- For small batch sizes, the machining process appears to be the best strategy.
- Tooling has a different influence within the two processes. In the forming one, *the tool manufacture has a relevant role in the environmental impact*, and such relevance increases with the decreasing of the batch size.



Results and discussion

- A Breakeven Point (BP) was identified for all the case studies. It is possible to notice that, in the worst scenario (aluminum recycling not considered), the BP is equal to 6 parts.
- This result is due to the fact that *the machined-off material has a higher environmental impact*.
- When the environmental burden ascribed to the machined-off material decreases, the BP increases up to becoming infinite in case of solid bonding recycling.



Conclusions and outlooks

- The results of a comparison between machining and forming have been presented.
- The research regarded an in-depth analysis on the recycling-related issues. The effects of the recycling strategy on the product life cycle environmental impact have been analyzed.
- The advantages deriving from solid state recycling techniques have been quantified.
- The influence of recycling policy on the Breakeven Point (batch size for which the environmental impact of different manufacturing approaches is exactly the same) has been discussed.
- Overall, the more efficient is the recycling process, the more advantageous the machining approach is.
- *The research therefore highlights the relevance of finding out innovative and efficient recycling strategies in order to lower the overall environmental impact of a product.*

References and further readings

- Priarone P.C., Ingarao G., Settineri L., Di Lorenzo R.

  On the impact of recycling strategies on energy demand and CO_2 emissions when manufacturing Al-based components

  Procedia CIRP (2016) Paper In Press

Environmental and economic process comparison

The role of additive manufacturing

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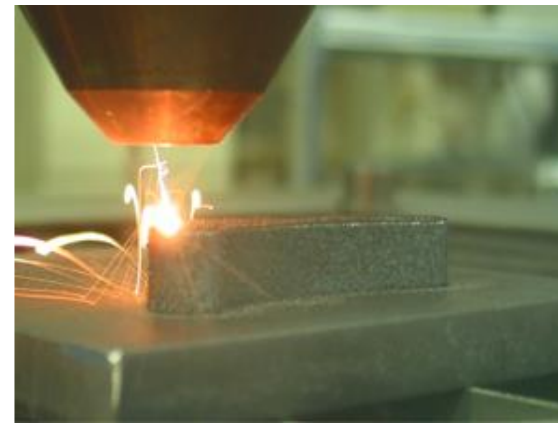
Introduction

- Additive manufacturing processes (particularly for metal parts) are promising candidates to work alongside the traditional manufacturing routes.
- The environmental footprint of additively manufactured parts has still to be fully understood. Moreover, there is the need to standardize the international research efforts in order to make the obtained results comparable.
- Studies quantifying the energy use (throughout the whole life cycle) and the GHG emission implications of additively manufactured components are currently scarce, and the researches have mostly considered polymeric materials.
- Besides the direct energy intensity of AM processes, material-related environmental impacts have to be included when considering cradle-to-grave boundaries.
- <u>Comparative analyses</u> are suitable to understand the actual environmental impact of different manufacturing approaches. However, such kind of studies is barely applied until now.
- Technological solutions for <u>integrating</u> different processes have to be investigated together with the environmental and economic impact assessment.



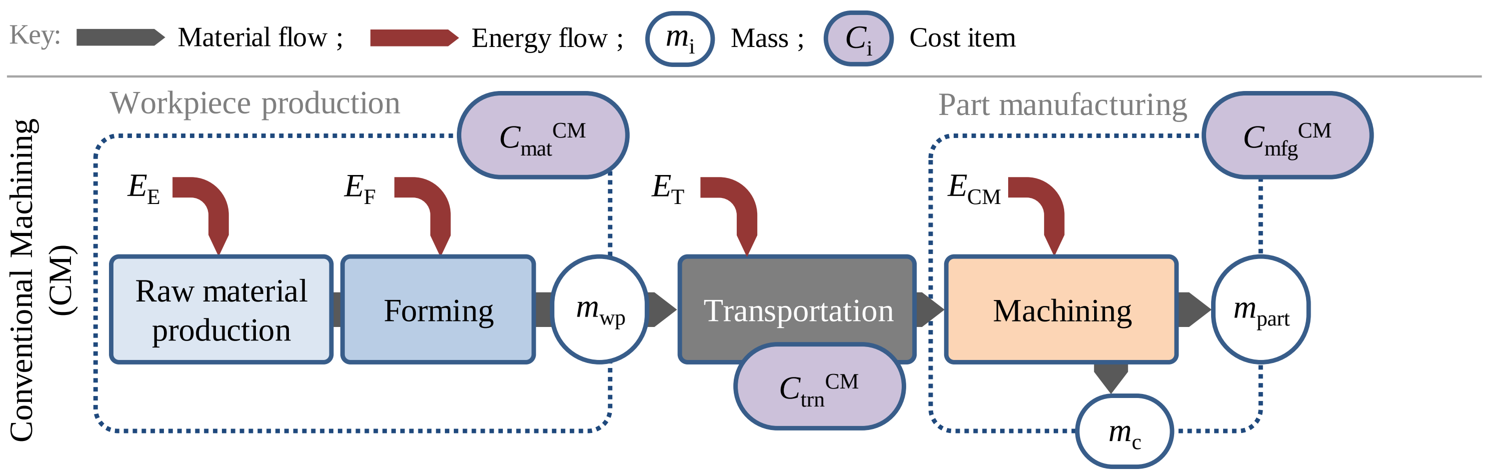
Additive Manufacturing

- Specific Energy Consumption for AM

Process	Material	SEC [MJ/kg]	Reference
DMLS	Stainless Steel	280,00 ÷ 280,00	Baumers et al.
	Stainless Steel 17-4 PH	241,00 ÷ 339,01	Baumers et al.
EBM	Ti6Al4V	61,20 ÷ 177,00	Baumers et al.
FDM	ABS	83,09 ÷ 1247,04	Luo et al.
	Polycarbonate	519,00 ÷ 636,00	Baumers et al.
SLA	Liquid photopolymer	74,52 ÷ 148,97	Luo et al.
SLM	Stainless Steel 316L	97,20 ÷ 139,50	Baumers et al.
	Stainless Steel 316L	111,60 ÷ 139,50	Baumers et al.
	Stainless Steel 316L	83,00 ÷ 106,00	Baumers et al.
	Stainless Steel 316L	96,84 ÷ 96,84	Baumers et al.
SLS	Nylon	130,00 ÷ 130,00	Telenko and Seepersad
	Nylon	107,39 ÷ 144,32	Luo et al.
	Nylon 12	52,20 ÷ 52,20	Screenivasan and Bourell
	PA 12	107,00 ÷ 4849,00	Baumers et al.
	Polyamide	107,39 ÷ 144,32	Luo et al.
	Polycarbonate	107,39 ÷ 144,32	Luo et al.
	Polymer	107,39 ÷ 144,32	Luo et al.
	Polymer	129,96 ÷ 129,96	Kellens et al.

Adding and taking away

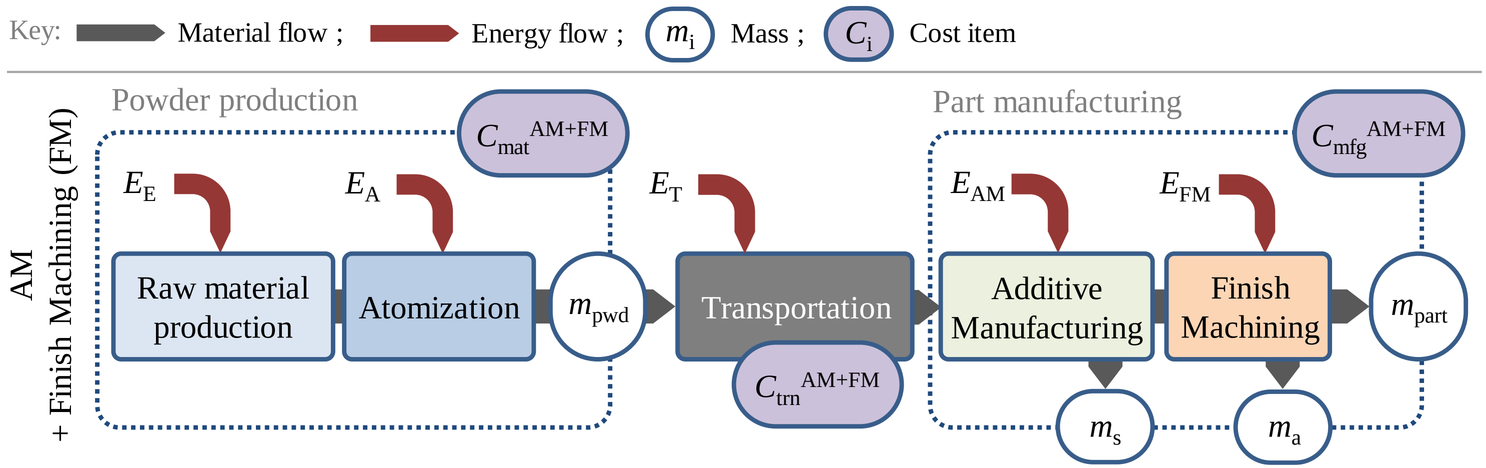
- Cradle-to-gate system boundary: *Conventional Machining* (CM)



- The finished part (weighting m_{part}) is produced by removing from a workpiece (weighting m_{wp}) the excess material in the form of chips (weighting m_c).
- The machining operations consume primary energy (E_{CM}) due to the resource demands of cutting and auxiliary processes, and result in a cost for manufacturing (C_{mfg}^{CM}).
- The workpiece is made out of an in-stock, available material (characterized by a certain value of embodied energy E_E), by means of a forming process (requiring an energy E_F) needed to achieve the geometry of the semi-finished product (i.e., a bar, a billet, a block, etc.).
- The workpiece has a cost (C_{mat}^{CM}) usually defined by the market rules.

From cradle to gate

- Cradle-to-gate system boundary: *Additive Manufacturing (EBM)* + *Finish Machining* (AM+FM)



- The part manufacturing stage is carried out via two subsequent steps: the AM (i.e., *EBM*) process creates the near-net-shape component with a superimposed machining allowance, which has to be then removed via FM.
- The mass of the required metal powder (m_{pwd}) for Additive Manufacturing (AM) should comprise the masses of the finished part (m_{part}), the process scraps (m_s), and the allowance (m_a) for the finish machining (FM) operation.
- The energy for the metal powder atomization process (E_A) has to be added to that of the raw material production (E_E).
- Both the energy requirements of AM (E_{AM}) and FM (E_{FM}) have to be included.
- The costs for the powder purchase (C_{mat}^{AM+FM}) and for the part manufacturing (C_{mfg}^{AM+FM}) are the main cost drivers.

From cradle to gate

The CM and AM+FM routes could be compared only if all the manufactured parts comply with the same product specifications, guaranteeing the same in-use performance.

This hypothesis is supported by the literature, since EBM processes have proved to produce fully-dense parts, whose mechanical properties could be matched with those of traditionally manufactured components.

Energy demand assessment

- Total energy demand (E_{tot}^{CM}, in MJ/part) for *Conventional Machining* (CM):

$$E_{tot}^{CM} = \overbrace{m_{wp} \cdot (E_E + E_F)}^{Workpiece\ production} + \overbrace{E_T \cdot m_{wp} \cdot d^{CM}}^{Transportation} + \overbrace{m_c \cdot S_E^{CM}}^{Manufacturing}$$

Where:

E_E (MJ/kg)	Embodied energy of the raw material
E_F (MJ/kg)	Energy for forming the workpiece
E_T (MJ/kg·km)	Energy penalty for transportation
S_E^{CM} (MJ/kg)	Specific energy demand per kg of removed material
m_{wp} (kg)	Mass of the workpiece (for CM: $m_{wp} = m_{part} + m_c$)
m_c (kg)	Mass of the machined chips
d^{CM} (km)	Distance travelled during transportation

- The S_E^{CM} value, which refers to the primary energy demand, could be obtained using either *black-box* (as the SEC model proposed by Kara and Li, 2011) or *bottom-up* approaches (e.g., Priarone et al., 2016).
- When accounting for the material production, the recycling benefit awarding should be included by applying the *recycled content approach* or the *substitution method*, according to Hammond and Jones (2010).

Energy demand assessment

- Total energy demand (E_{tot}^{AM+FM}, in MJ/part) for *Additive Manufacturing* (AM) + *Finish Machining* (FM):

$$E_{tot}^{AM+FM} = \overbrace{m_{pwd} \cdot (E_E + E_A)}^{Powder\ production} + \overbrace{E_T \cdot m_{pwd} \cdot d^{AM+FM}}^{Transportation} + \overbrace{\boxed{m_{pwd} \cdot S_E^{AM}} + \boxed{m_a \cdot S_E^{FM}}}^{Manufacturing}$$

Where:

E_E (MJ/kg)	Embodied energy of the raw material
E_A (MJ/kg)	Energy for powder atomization
E_T (MJ/kg·km)	Energy penalty for transportation
S_E^{AM} (MJ/kg)	Specific energy demand per kg of deposited material (for AM)
S_E^{FM} (MJ/kg)	Specific energy demand per kg of removed material (for FM)
m_{pwd} (kg)	Mass of the metal powder (for AM: $m_{pwd} = m_{part} + m_s + m_a$)
m_s (kg)	Mass of the support structures
m_a (kg)	Mass of the machining allowance
d^{AM+FM} (km)	Distance travelled during transportation

- The energy contributions for (*i*) additively manufacture the near-net-shape metal part, and for (*ii*) removing the machining allowance have to be both considered.
- Full machine capacity utilization.

From cradle to gate: Cost assessment

- Total cost model (C_{tot}^{CM}, in MJ/part) for *Conventional Machining* (CM):

$$C_{tot}^{CM} = \overbrace{m_{wp} \cdot C_{wp}}^{Workpiece\ purchase} + \overbrace{C_T \cdot m_{wp} \cdot d^{CM}}^{Transportation} + \overbrace{m_c \cdot \boxed{S_C^{CM}}}^{Manufacturing}$$

$$S_C^{CM} = \frac{\dot{C}_{ind}^{CM}}{MRR} + C_{dir}^{CM} = \frac{\dot{C}_{ind}^{CM}}{MRR} + C_{EE} \cdot SEC^{CM}$$

Where:

C_{wp} (€/kg)	Cost of the workpiece material
m_{wp} (kg)	Mass of the workpiece (for CM: $m_{wp} = m_{part} + m_c$)
C_T (€/kg·km)	Cost for transportation
d^{CM} (km)	Distance travelled during transportation
S_C^{CM} (€/kg)	Specific cost per kg of removed material
m_c (kg)	Mass of the machined chips
$\dot{C}_{ind}^{CM}$ (€/h)	Total indirect cost rate
C_{dir}^{CM} (€/kg)	Total direct costs, per unit mass
MRR (kg/h)	Material Removal Rate
C_{EE} (€/kWh)	Cost of electric energy
SEC^{CM}	Specific electric energy consumption

- The costs for CM are related to (*i*) machine tools, devices, fixtures and cutting tools; (*ii*) labor and overhead; (*iii*) material handling and movement; (*iv*) gaging for dimensional accuracy and surface finish; (*v*) cutting and non-cutting times.
- The total cost per produced part is the sum of fixed costs and variable costs depending on process parameters.

From cradle to gate: Cost assessment

- Total cost model (C_{tot}^{AM+FM}, in MJ/part) for *Additive Manufacturing* (AM) + *Finish Machining* (FM):

$$C_{tot}^{AM+FM} = \overbrace{m_{pwd} \cdot C_{pwd}}^{Powder\ \ purchase} + \overbrace{C_T \cdot m_{pwd} \cdot d^{AM+FM}}^{Transportation} + \overbrace{\boxed{m_{pwd} \cdot S_C^{AM}} + \boxed{m_a \cdot S_C^{FM}}}^{Manufacturing}$$

Where:

C_{pwd} (€/kg)	Cost of the metal powder
m_{pwd} (kg)	Mass of the metal powder ($m_{pwd} = m_{part} + m_s + m_a$)
C_T (€/kg·km)	Cost for transportation
d^{AM+FM} (km)	Distance travelled during transportation
S_C^{AM} (€/kg)	Specific cost per kg of deposited material (for AM)
S_C^{FM} (€/kg)	Specific cost per kg of removed material (for FM)
m_a (kg)	Mass of the machining allowance

- As for the previous models, the cost for the post-AM finishing operation has been included.
- S_C^{AM} must involve both direct costs and indirect cost rate, as proposed in Baumers et al. (2016).

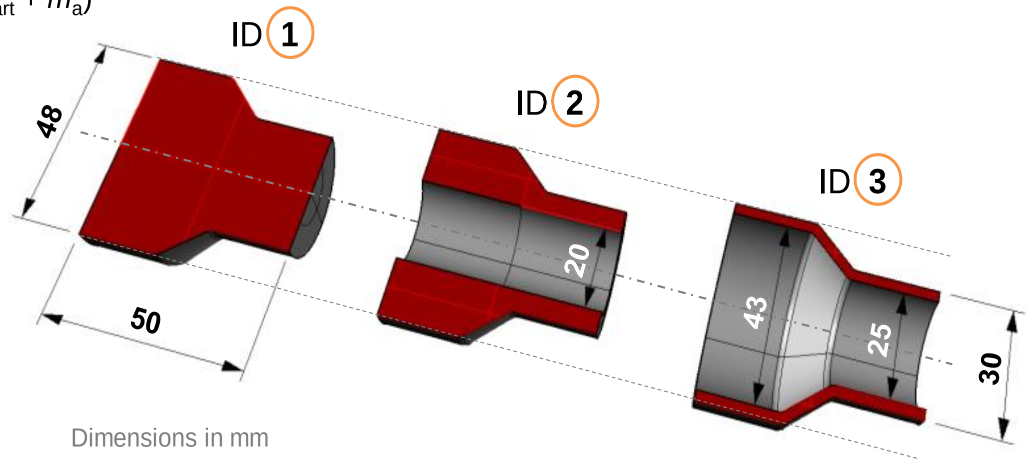
From cradle to gate: Case study

- Different *solid-to-cavity ratios* (from ID 1 to ID 3) have been assumed in order to vary the amount of process scraps for subtractive approaches (i.e., for CM).
- Main assumptions → Material: Ti-6Al-4V
  - *Conventional Machining:*

    Workpiece: bar (diameter = 50 mm, length = 50 mm)
  - *Additive Manufacturing:*

    Machining allowance: 1-mm thick (constant)

    Mass of the support structures: 15% of (m_{part} + m_a)



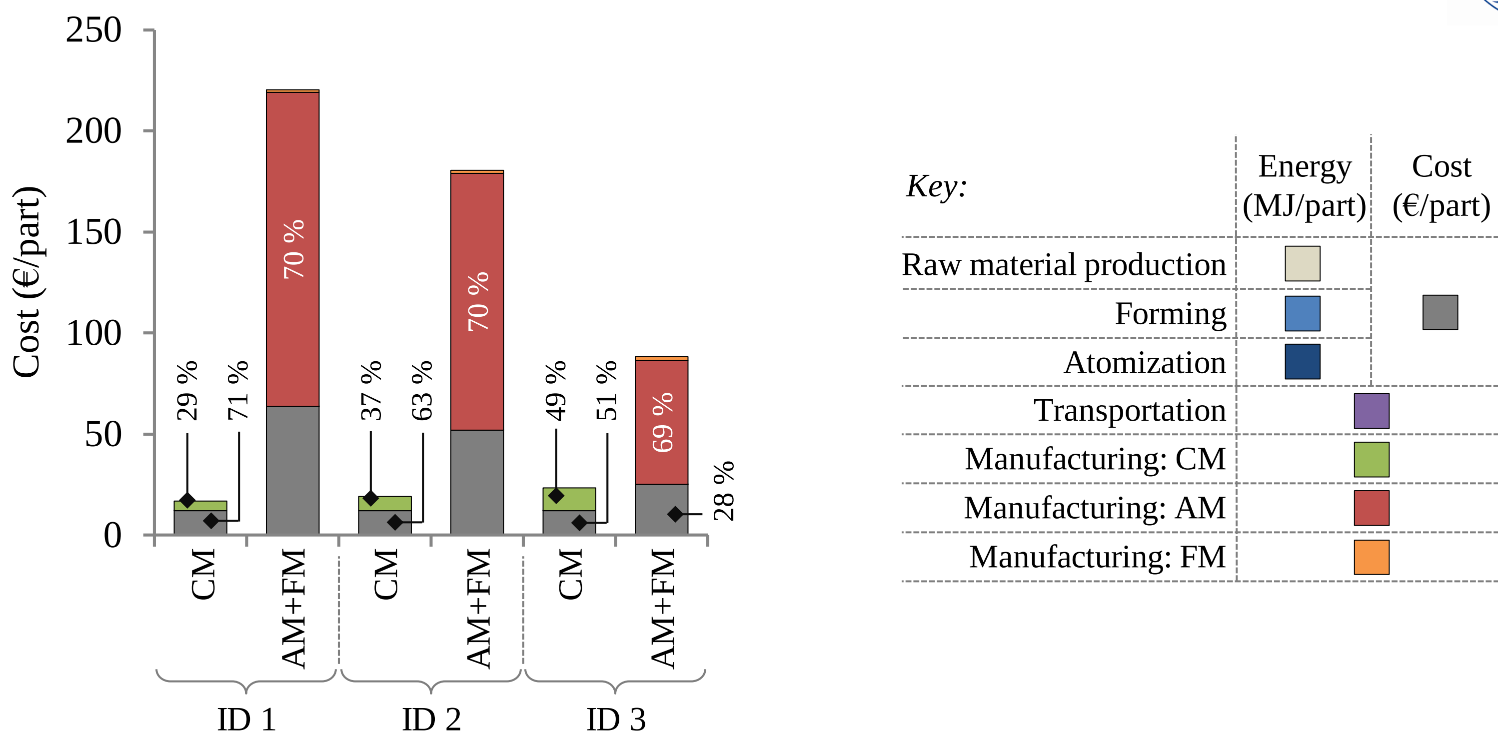
Dimensions in mm

		CM		AM+FM		
ID	m_{part} (kg)	m_c (kg)	m_{wp} (kg)	m_a (kg)	m_s (kg)	m_{pwd} (kg)
1	0.275	0.157	0.432	0.042	0.048	0.364
2	0.206	0.226	0.432	0.053	0.039	0.298
3	0.067	0.365	0.432	0.058	0.019	0.144

From cradle to gate: Life Cycle Inventory

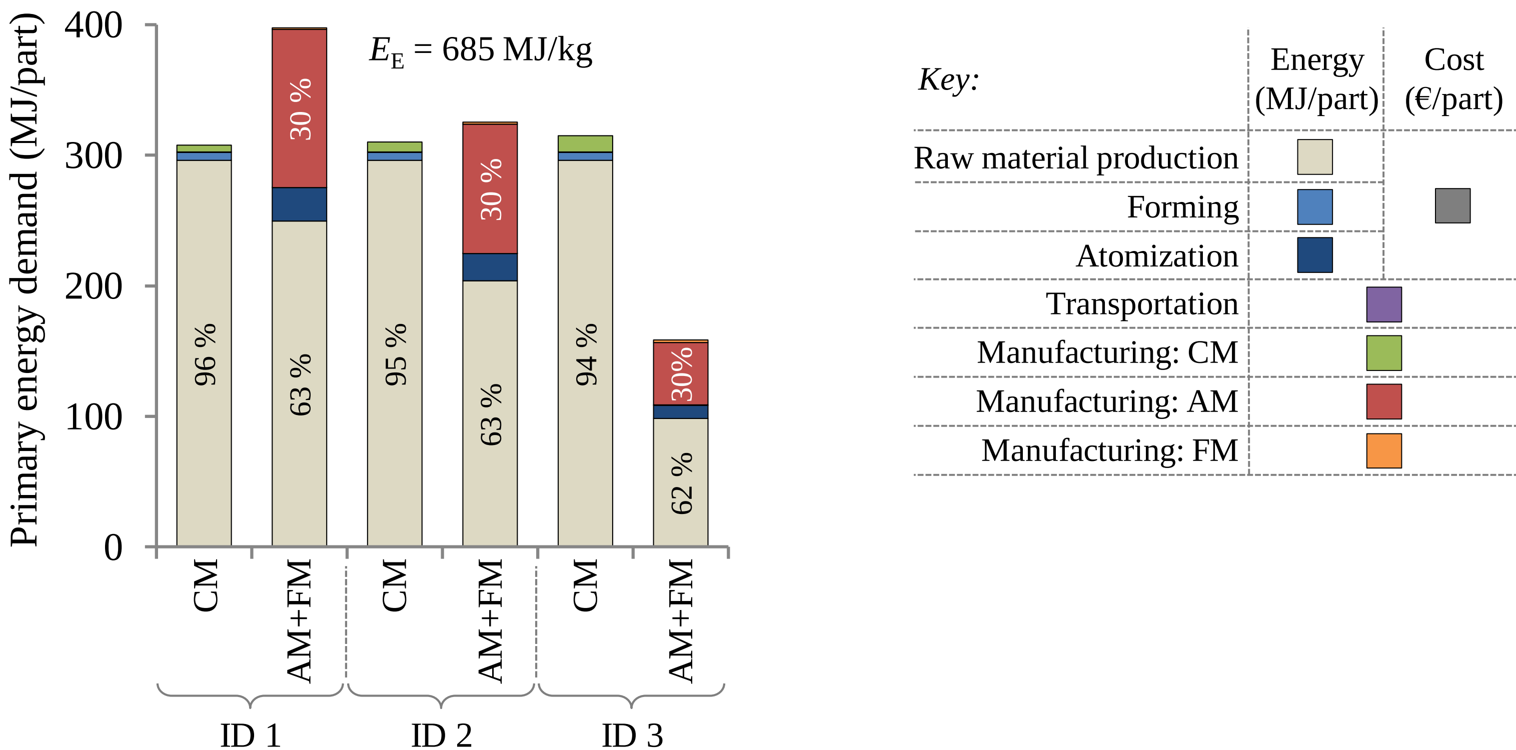
<table>
<tr><th></th><th>CM</th><th>AM+FM</th></tr>
<tr><td rowspan="3">Material</td><td colspan="2">E_E = 206.6 or 685.0 MJ/kg
(Ashby, 2013; Priarone et al., 2016)</td></tr>
<tr><td>E_F = 14.5 MJ/kg
(Ashby, 2013)</td><td>E_A = 70.0 MJ/kg
(adapted from Paris et al., 2016)</td></tr>
<tr><td>C_{wp} = 28.0 €/kg
(Hällgren et al., 2016)</td><td>C_{pwd} = 175.0 €/kg
(adapted from Baumers et al., 2016)</td></tr>
<tr><td rowspan="3">Transportation</td><td colspan="2">$E_T = 0.94 \cdot 10^{-3}$ MJ/kg·km (Ashby, 2013)</td></tr>
<tr><td colspan="2">$C_T = 0.025 \cdot 10^{-3}$ €/kg·km (adapted from Qu et al., 2016)</td></tr>
<tr><td colspan="2">$d^{CM} = d^{AM+FM}$ = 300 km (EcoInvent, 2012)</td></tr>
<tr><td rowspan="3">Process</td><td>S_E^{CM} = 34.5 MJ/kg
(adapted from Priarone et al., 2016,
for MRR = 2.5 kg/h and SEC = 9.9 kWh/kg)</td><td>S_E^{AM} = 332.0 MJ/kg
(adapted from Baumers et al., 2016)
$S_E^{FM} = S_E^{CM}$</td></tr>
<tr><td>S_C^{CM} = 31.3 €/kg
(with $\dot{C}_{ind}^{CM}$ = 76.6 €/h,
adapted from Schultheiss et al., 2016)</td><td>S_C^{AM} = 426.2 €/kg
(adapted from Baumers et al., 2016)
$S_C^{FM} = S_C^{CM}$</td></tr>
<tr><td colspan="2">C_{EE} = 0.072 €/kWh (adapted from Baumers et al., 2016)</td></tr>
</table>

From cradle to gate: Results and Discussion



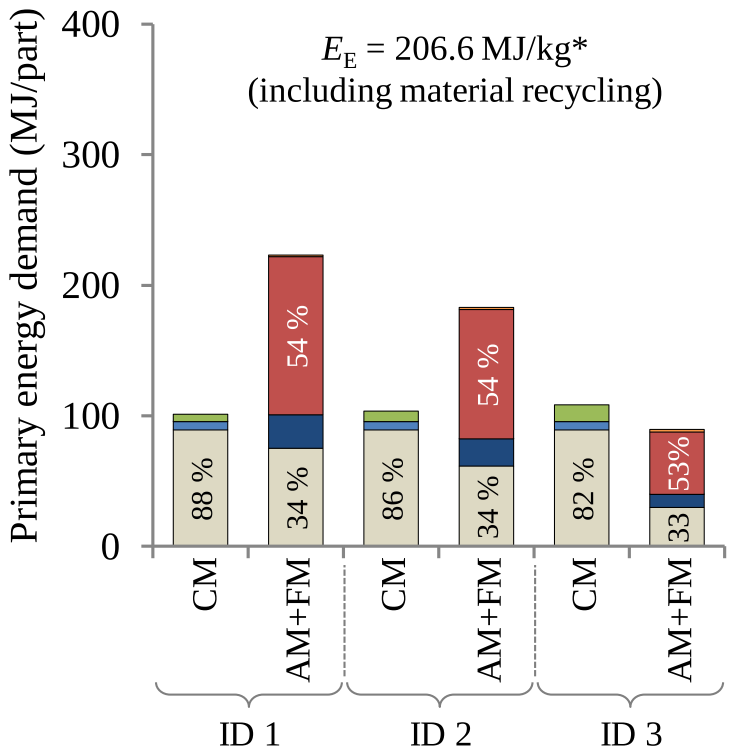
- Although the masses of material involved in the AM+FM approach are always lower than those of CM, the workpiece and powder costs are significantly different (C_{wp} = 28.0 €/kg versus C_{pwd} = 175.0 €/kg).
- The material purchase is the main cost item for CM, while for AM+FM the total cost per part is dominated by the EBM process, and the post-process finish machining operation (FM) cost appears to be small. The specific cost per unit mass of AM (S_C^{AM} = 426.2 €/kg) is one order of magnitude higher than that of CM (S_C^{CM} = 31.3 €/kg).
- This is mainly due to the longer duration of the AM process, since (*i*) the directs costs related to the electric energy consumption are basically negligible for both the approaches, and (*ii*) the assumed total indirect cost rate favors AM ($\dot{C}_{ind}^{AM}$ = 29.4 €/h) instead of CM ($\dot{C}_{ind}^{CM}$ = 76.6 €/h).

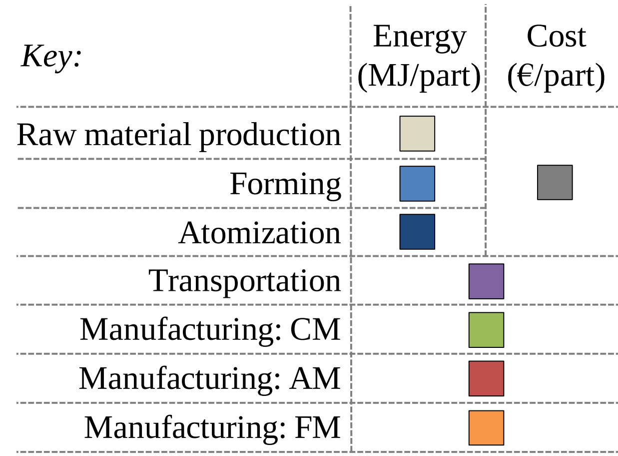
From cradle to gate: Results and Discussion



- ❑ Both the energy demands and the costs are heavily affected by the material usage. When enabling significant material savings, the AM+FM approach appears to be the best strategy from the primary energy saving viewpoint.
- ❑ This outcome is particularly remarkable when the benefits of material recycling are NOT accounted for.

From cradle to gate: Results and Discussion





* Note: Value computed by applying the *substitution method*, and assuming:

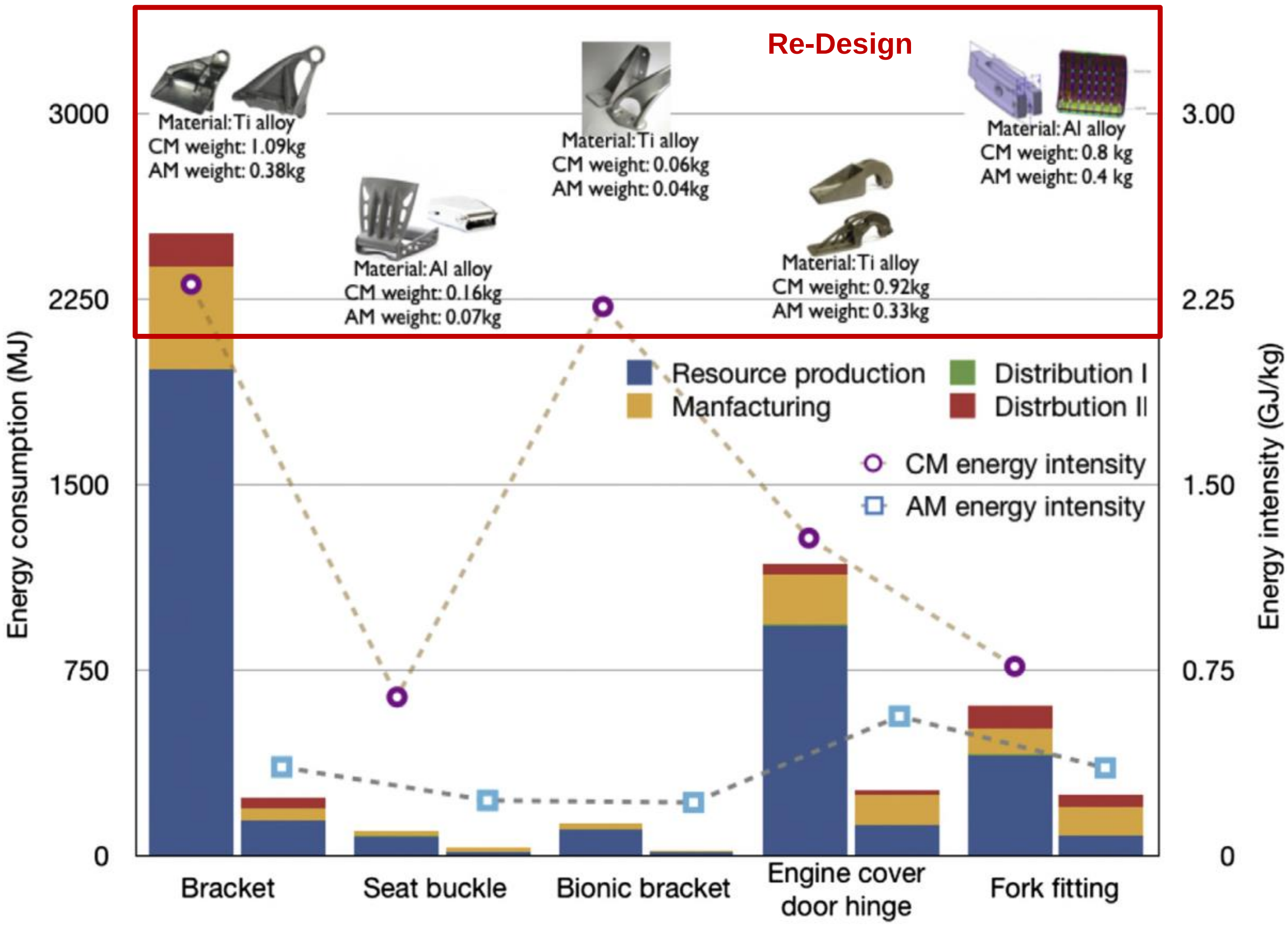
- Energy for recycling: 87 MJ/kg
- Material recyclability: 0.80

- ❑ The impact of material usage dominates the energy breakdown, therefore the benefits of material recycling appears to be of primary importance.
- ❑ On the other hand, when a small amount of material has to be machined-off (i.e., for ID 1), the high energy intensity of the EBM process has a negative effect on the AM energy-intensity performance.

Think Additive

Cradle-to-gate primary energy results for aerospace components.

Huang et al. (2015)

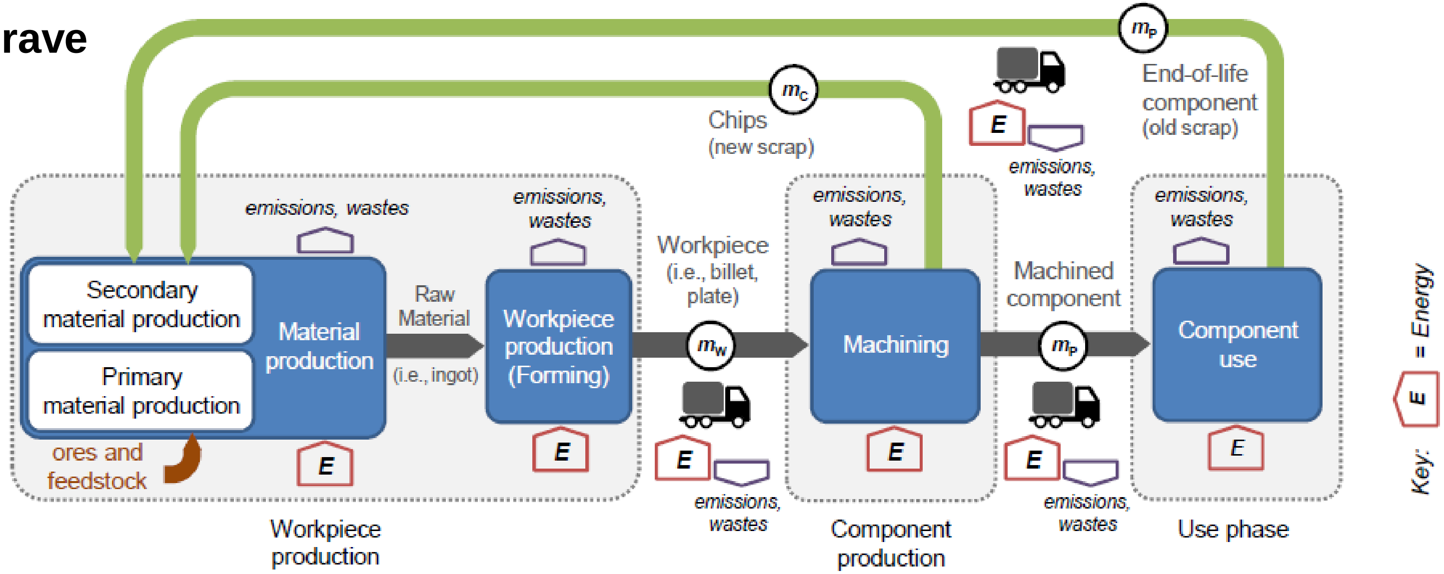


Energy saving potential of AM technologies compared to CM technologies.

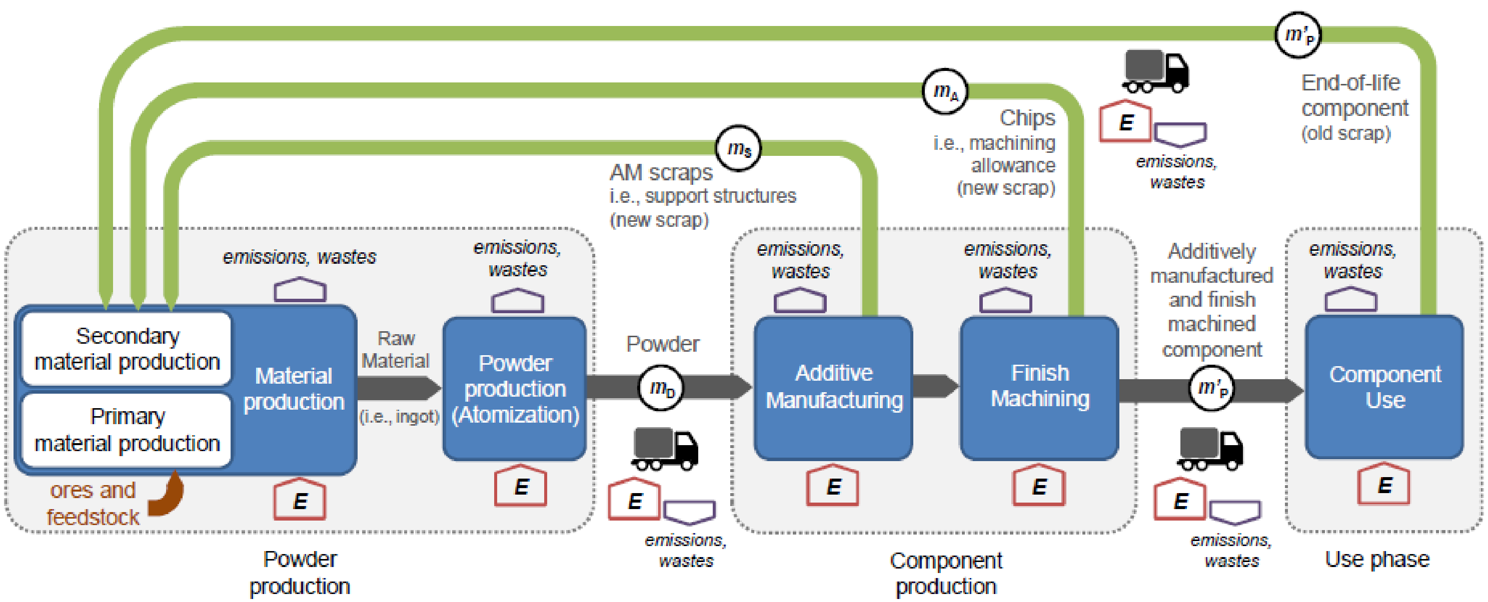
For each component, the AM pathway led to significantly lower cradle-to gate primary energy use compared to the CM pathway.

These energy savings are primarily due to the **(1)** reductions in resource production energy use attributable to the lower buy-to-fly ratios of AM processes and the **(2)** reduced mass associated with the AM components' advanced lightweight geometries.

From cradle to grave



- Use phase
- Light-weighting
- Recycling



Priarone, Ingarao (2017)

From cradle to grave

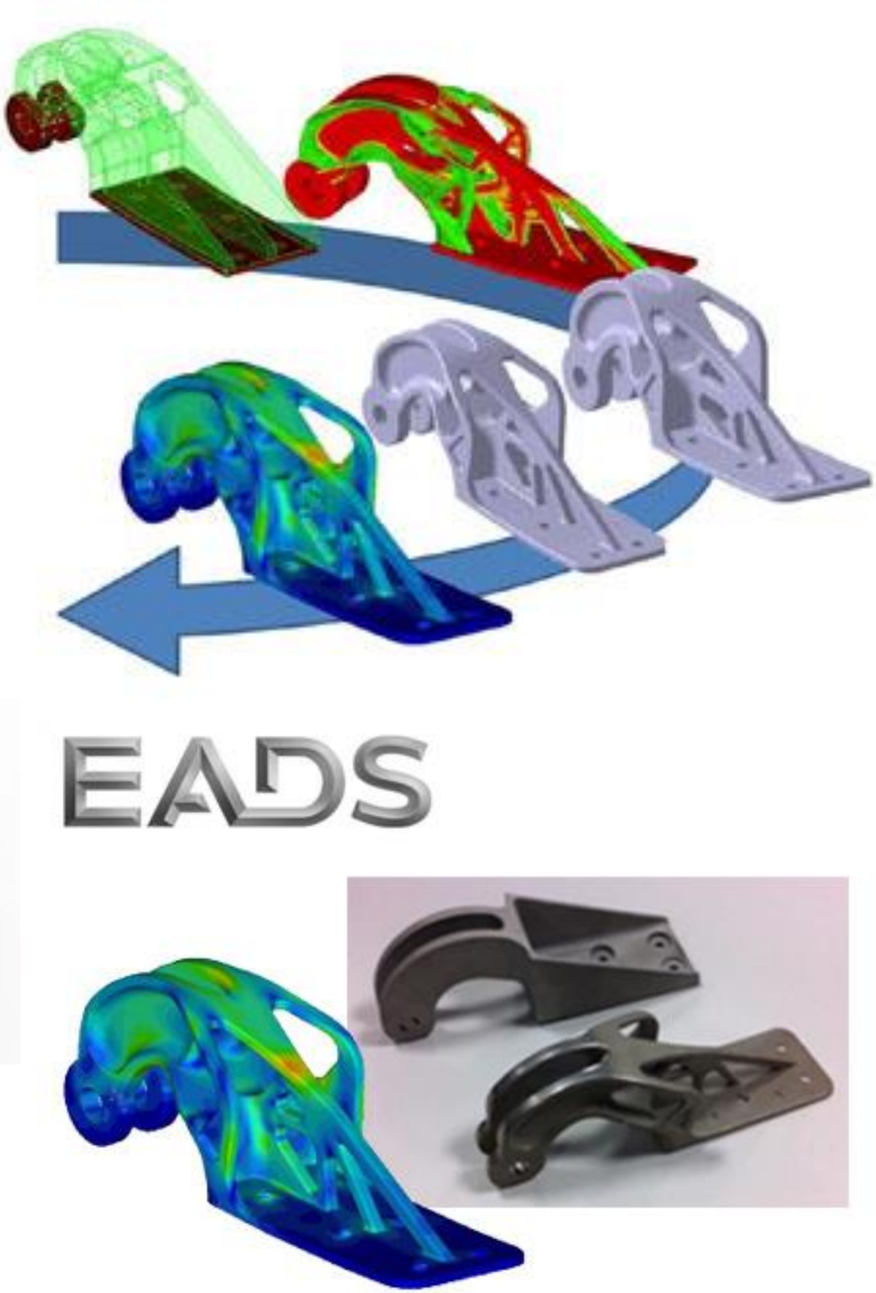
- Total energy demand *(E^{CM}*, in MJ/part) for *Conventional Machining*

$$E^{CM} = \overbrace{(m_P + m_C)\cdot(E_E + E_F)}^{E^{CM}_{MAT}} + \overbrace{m_C \cdot U_E^{CM}}^{E^{CM}_{MFG}} + \overbrace{E_T \cdot [(m_P + m_C)\cdot d_1 + m_P \cdot d_2 + m_C \cdot d_3 + m_P \cdot d_4]}^{E^{CM}_{TRN}} + \boxed{E^{CM}_{USE}} \quad \left(\frac{MJ}{part}\right)$$

- Total energy demand *(E^{AM+FM}*, in MJ/part) for *Additive Manufacturing* + *Finish Machining*

$$E^{AM+FM} = \overbrace{(\boxed{k\cdot m_P} + m_A + m_S)\cdot(E_E + E_A)}^{E^{AM+FM}_{MAT}} + \overbrace{(k\cdot m_P + m_A + m_S)\cdot U_E^{AM} + m_A \cdot U_E^{CM}}^{E^{AM+FM}_{MFG}} + \overbrace{E_T \cdot [(k\cdot m_P + m_A + m_S)\cdot d_1' + k\cdot m_P \cdot d_2 + (m_A + m_S)\cdot d_3 + k\cdot m_P \cdot d_4]}^{E^{AM+FM}_{TRN}} \boxed{+ E^{AM+FM}_{USE}} \quad \left(\frac{MJ}{part}\right)$$

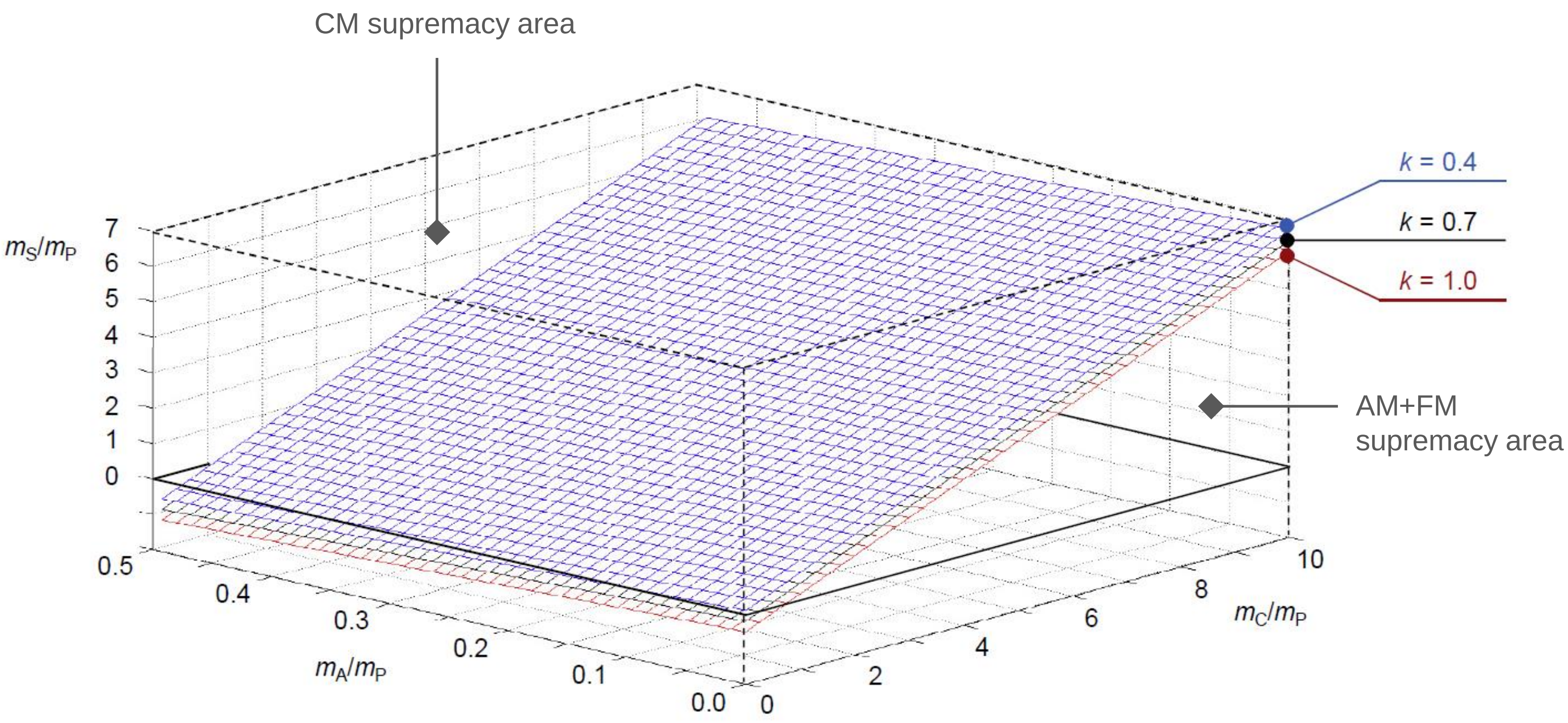
Light-weighing



Effects of light-weighing

- *Material production + Manufacturing phase*

$$E^{CM} = E^{AM+FM}$$

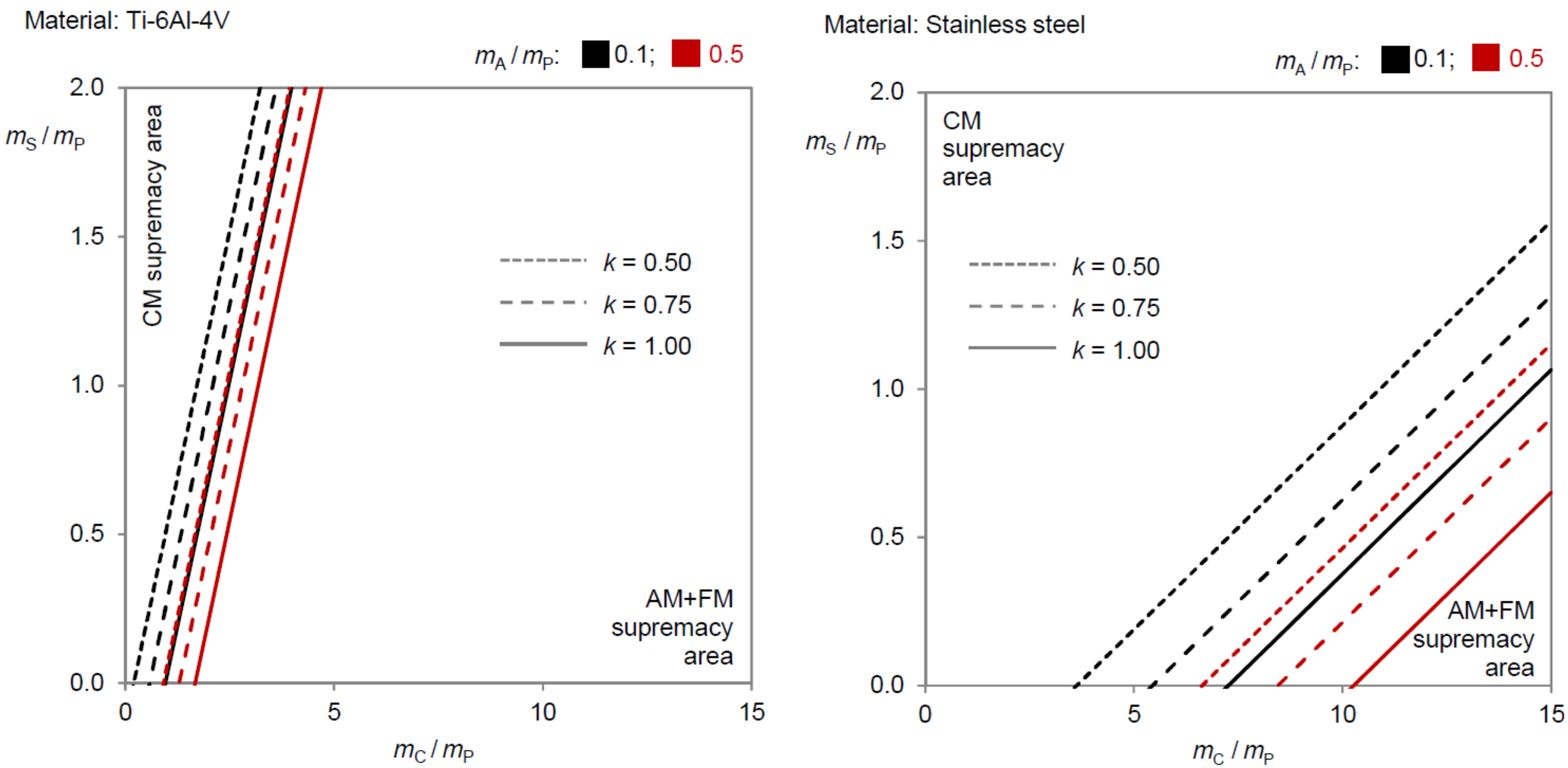


Iso-energy planes for the cradle-to-gate plus end-of-life analysis of a Ti-6Al-4V component production, *as a function of the k value*

Priarone, Ingarao (2017)

Effects of light-weighing

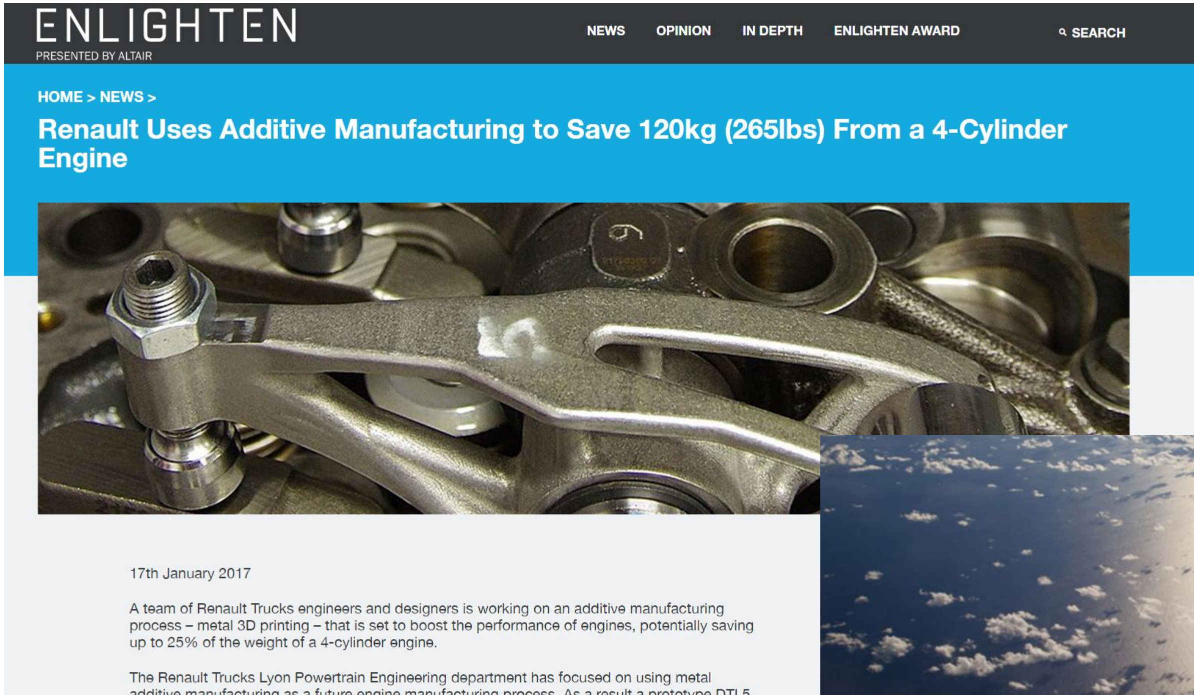
- *Material production + Manufacturing phase*



Cross-sections of the Ti-6Al-4V and stainless steel component production iso-energy planes

Priarone, Ingarao (2017)

Effects of light-weighing



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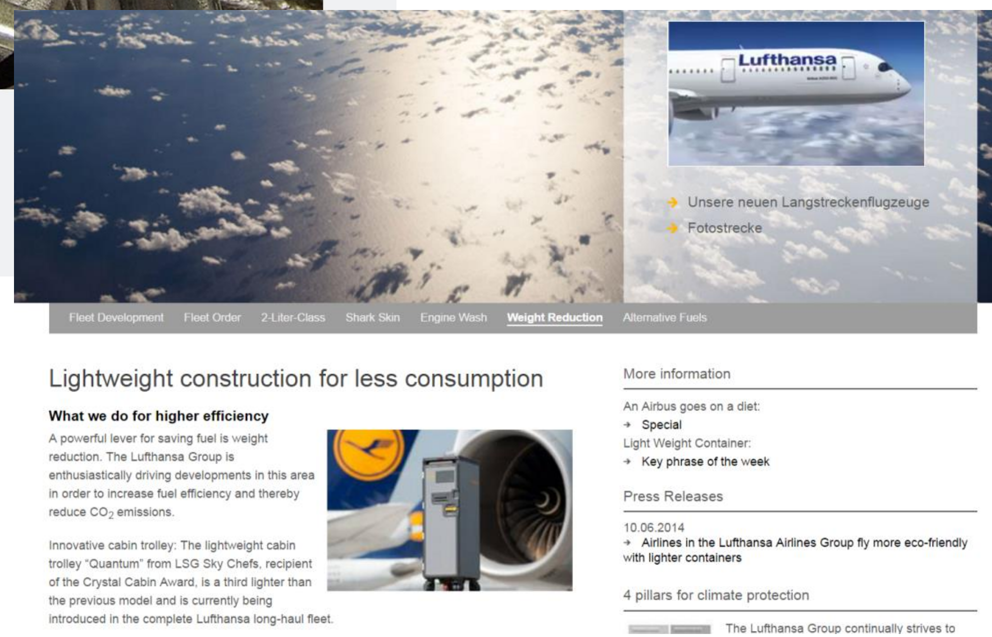
Renault Uses Additive Manufacturing to Save 120kg (265lbs) From a 4-Cylinder Engine

17th January 2017

A team of Renault Trucks engineers and designers is working on an additive manufacturing process – metal 3D printing – that is set to boost the performance of engines, potentially saving up to 25% of the weight of a 4-cylinder engine.

The Renault Trucks Lyon Powertrain Engineering department has focused on using metal additive manufacturing as a future engine manufacturing process. As a result a prototype DTI 5



Unsere neuen Langstreckenflugzeuge
Fotostrecke

Fleet Development | Fleet Order | 2-Liter-Class | Shark Skin | Engine Wash | Weight Reduction | Alternative Fuels

Lightweight construction for less consumption

What we do for higher efficiency

A powerful lever for saving fuel is weight reduction. The Lufthansa Group is enthusiastically driving developments in this area in order to increase fuel efficiency and thereby reduce CO_2 emissions.

Innovative cabin trolley: The lightweight cabin trolley "Quantum" from LSG Sky Chefs, recipient of the Crystal Cabin Award, is a third lighter than the previous model and is currently being introduced in the complete Lufthansa long-haul fleet.

More information

An Airbus goes on a diet:
→ Special
Light Weight Container:
→ Key phrase of the week

Press Releases

10.06.2014
→ Airlines in the Lufthansa Airlines Group fly more eco-friendly with lighter containers

4 pillars for climate protection

The Lufthansa Group continually strives to

Effects of light-weighing on the use phase

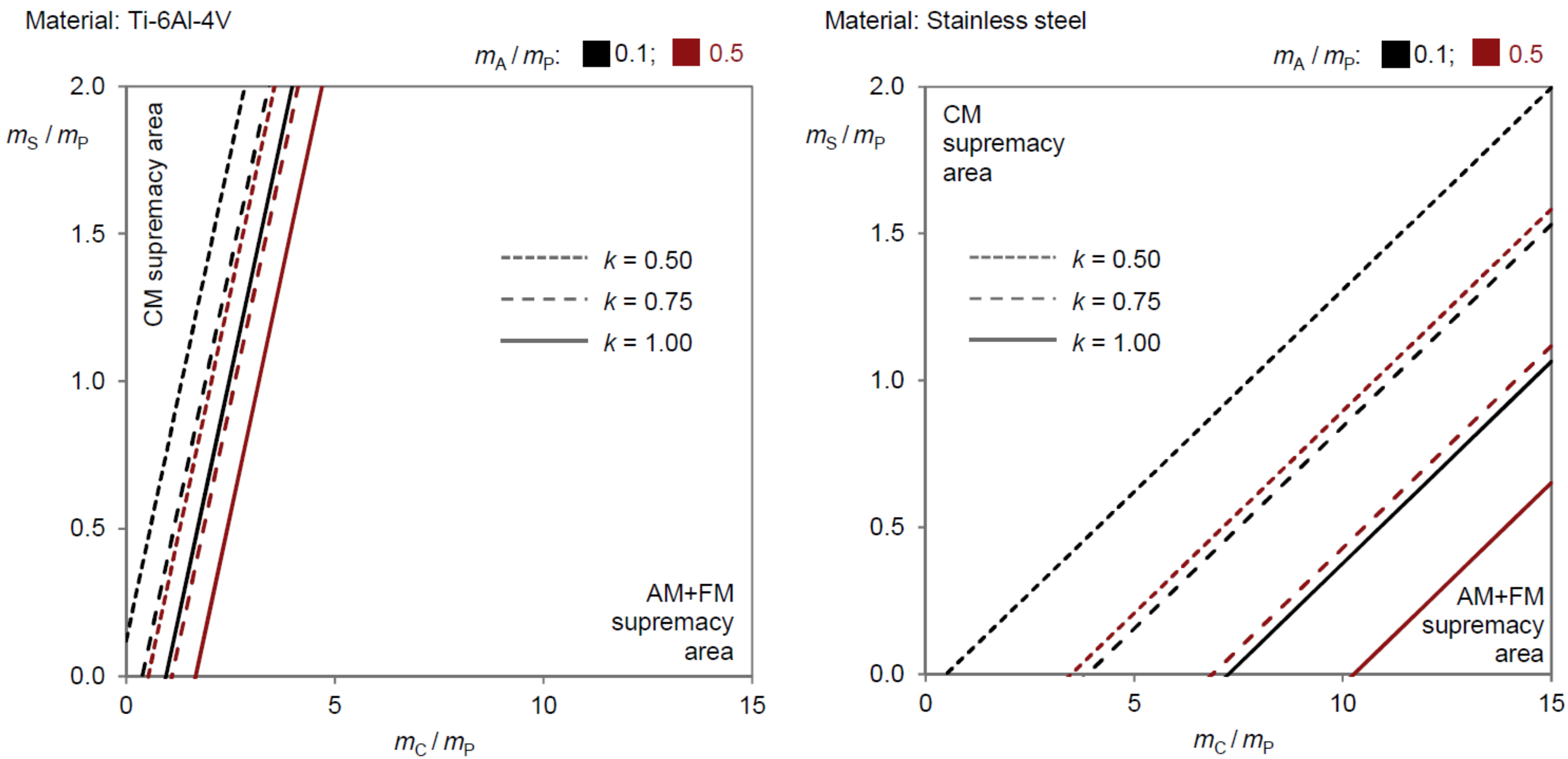
Vehicle type	Fuel	Use phase	Use phase energy savings per 1 kg of reduced weight
Passenger car	Gasoline	$0.2 \cdot 10^6$ km	230 MJ
Passenger car	Diesel	$0.2 \cdot 10^6$ km	210 MJ
Articulated truck	Diesel	$1.2 \cdot 10^6$ km	260 MJ
Short-distance aircraft	Kerosene	30 y	$150 \cdot 10^3$ MJ
Long-distance aircraft	Kerosene	30 y	$200 \cdot 10^3$ MJ

Vehicle type	Fuel	Use phase	Use phase CO_2 savings per 1 kg of reduced weight[a]
Passenger car	Gasoline	$0.2 \cdot 10^6$ km	15.0 kg
Passenger car	Diesel	$0.2 \cdot 10^6$ km	14.9 kg
Articulated truck	Diesel	$1.2 \cdot 10^6$ km	18.5 kg
Short-distance aircraft	Kerosene	30 y	$10.2 \cdot 10^3$ kg
Long-distance aircraft	Kerosene	30 y	$13.6 \cdot 10^3$ kg

Priarone, Ingarao (2017)

Effects of light-weighing on the use phase

- *Gasoline car*

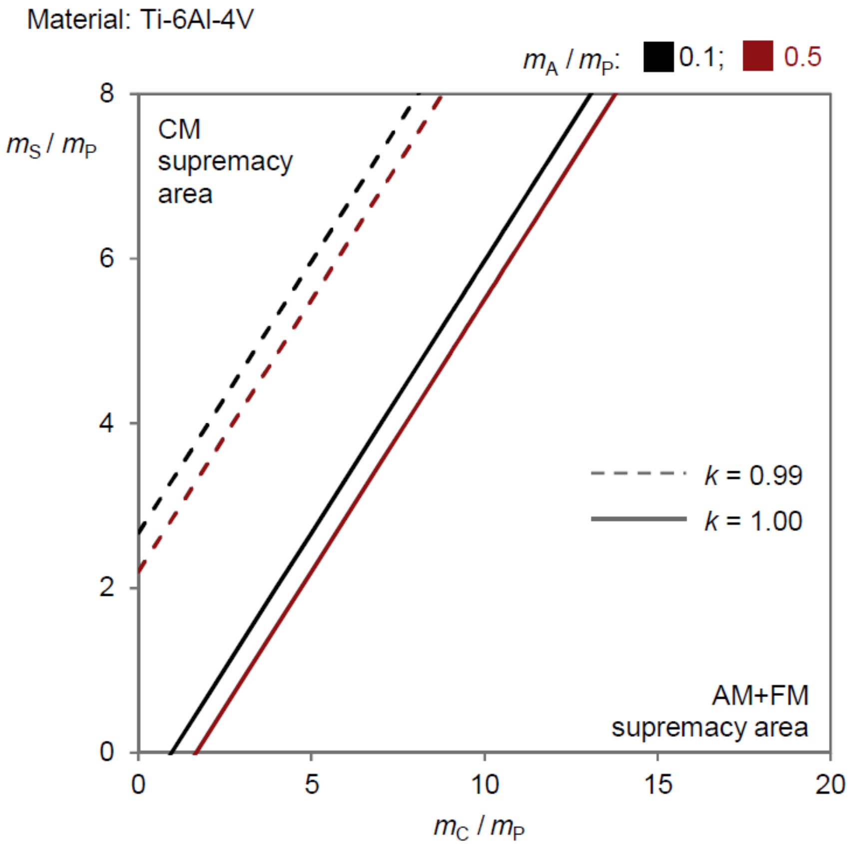


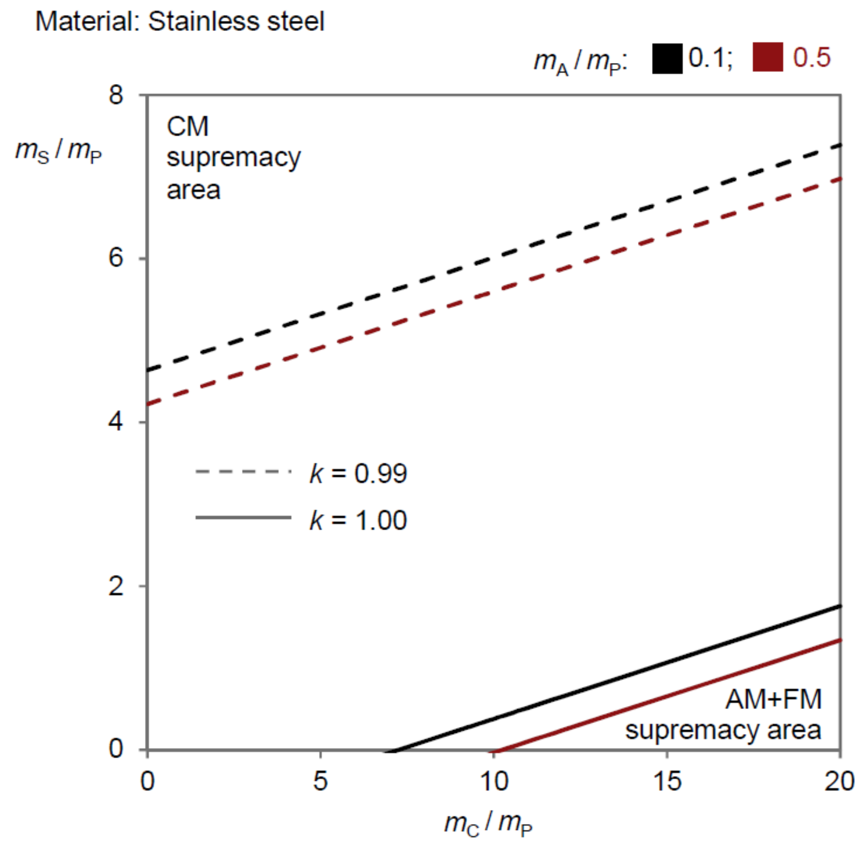
Cross-sections of the Ti-6Al-4V and stainless steel component production iso-energy planes

Priarone, Ingarao (2017)

Effects of light-weighing on the use phase

- *Short-distance aircraft*





Cross-sections of the Ti-6Al-4V and stainless steel component production iso-energy planes

Priarone, Ingarao (2017)

Summary

- It is not fair labeling a priori the AM or CM approach as cost- or energy-efficient, since the component features have to be also taken into account.

- Simple part geometries have been assumed as case study, since the basic idea was to analyze the impact related to material usage, and specifically (for CM) to the amount of the machined-off material with respect to the volume of the part.

- It is worth pointing out that AM has already shown his technological potential when creating complex geometries or parts redesigned for additive manufacturing (i.e., by means of topological optimization practices).

- The AM processes might enable new product design scenarios resulting in a substantial weight reduction. This can lead to a further reduction in material usage for the AM approaches over the CM ones, which would result in further energy and CO_2 emission resections.

- There is the need to stimulate the scientific debate on the environmental performance of processes. Such knowledge will enable new green manufacturing guidelines to be defined.

References and further readings

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  Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components

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  Towards criteria for sustainable process selection: On the modelling of pure subtractive versus additive/subtractive integrated manufacturing approaches

  Journal of Cleaner Production 144 (2017): 57-68

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  Assessment of Cost and Energy Requirements of Electron Beam Melting (EBM) and Machining Processes

  Smart Innovation, Systems and Technologies 68 (2017): 723-735