Process comparison: additive manufacturing vs. machining

Sustainable Manufacturing
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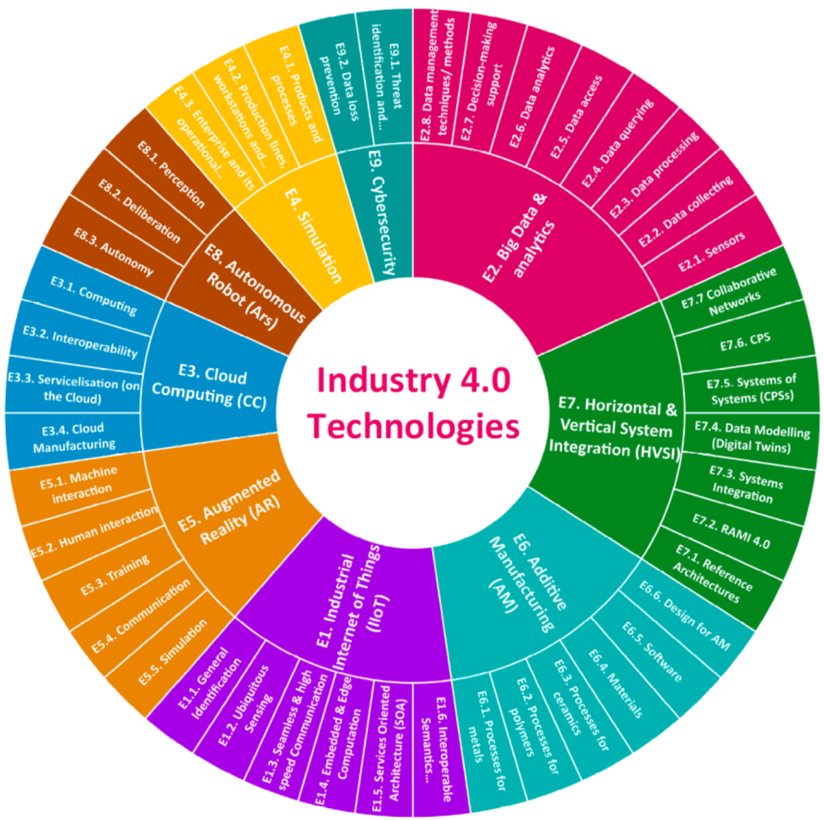
MAESTRO



I4.0 enablers and elements technologies.

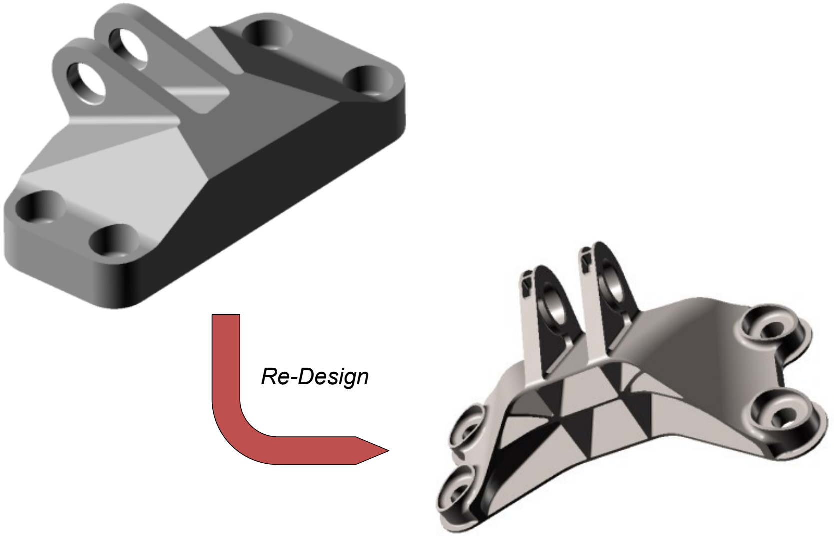
Source: https://doi.org/10.3390/su13052560

- **ILO**: Evaluate the environmental performance of different manufacturing approaches by modelling their sustainability through Life-Cycle Assessment and other state-of-the-art methodologies.

- Increase of sustainability awareness
- I4.0 impact on education profile of the students.

Additive versus subtractive manufacturing

- General Electric (GE) proposed in 2013 a competition for the sustainable re-design of a titanium lifting bracket for a jet aircraft engine, generating over 700 entries. The results of the challenge have been the source of inspiration for the impact comparison here discussed.
- Among all the optimized solutions, a re-designed component (suitable for an *EBM process*) allowing a weight reduction higher than 80% has been chosen.
- This case study is adequately representative of the weight-saving achievable by mathematical techniques, such as topology optimization, that optimize the material distribution within the design space under specific loading conditions.
- The original design envelop was hypothesized to be the part to be obtained by means of a *machining process*.
- The re-designed component weighs 0.34 kg (if made of a Ti-6Al-4V alloy), whereas the "original" component weighs 2.04 kg and could be obtained from a workpiece weighing 5.13 kg by means of milling.



Source: https://doi.org/10.1016/j.procir.2017.11.047

Life Cycle Inventory

- Commercial databases and/or the scientific literature provided the life cycle data for the assessment, as follows.
- **Material production:** The values of embodied energy (E_E) and carbon footprint (CO_{2E}) for a cast Ti-6Al-4V alloy, to be considered (*i*) for the sole primary material production or (*ii*) when including the recycling benefit awarding are listed in Table 1. The recycle fraction in the current supply is 0.22. The EoL recyclability can be assumed as high as 0.80, and equal for both process scraps and component material.
- **Pre-manufacturing:** To produce 1 kg of Ti-6Al-4V powder for an EBM process, Paris et al. (2016) have quantified a consumption of 6.6 kWh of electricity and 5.5 m^3 of Argon (resulting in a primary energy demand of 70 MJ/kg and related CO_2 emissions of 3.8 kg/kg), with a process efficiency of 97% (i.e., input/output material ratio, y_A = 1.03). Other authors (Baumers et al., 2016) quantified the energy consumed for the gas atomization route of Ti-6Al-4V in the range from 30.1 to 33.3 MJ/kg. Such data variability has been considered in this case study (Table 1).
- As for the workpiece production, the specific energy for material deformation and the carbon footprint were assumed to vary from 14 to 15 MJ/kg and from 1.1 to 1.2 kg/kg, respectively. The bulk forming process efficiency was supposed to be 94% (i.e., y_F = 1.06).

Table 1. Eco-properties for material production and pre-manufacturing

Eco-Property	Min	Max
Embodied energy, E_E (MJ/kg), primary production	653.0	720.0
CO_2 footprint, $CO_{2\,E}$ (kg/kg), primary production	38.3	42.2
Embodied energy, recycling (MJ/kg)	82.6	91.3
CO_2 footprint, recycling (kg/kg)	6.5	7.2
Energy demand for powder atomization, E_A (MJ/kg)	30.1	70.0
CO_2 footprint for powder atomization, $CO_{2\,A}$ (kg/kg)	1.6	3.8
Energy demand for workpiece forming, E_F (MJ/kg)	14	15
CO_2 footprint for workpiece forming, $CO_{2\,F}$ (kg/kg)	1.1	1.2

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Life Cycle Inventory

- **Manufacturing:** The specific electric energy demand for the Electron Beam Melting of Ti-6Al-4V has been quantified within the range 60-177 MJ/kg (for an Arcam machine) by Baumers and colleagues (2011, 2016). After the build completion, finishing operations are needed to disconnect the parts from the plate and to remove the support structures. The traditional mechanical removal - which is considered here - causes an almost negligible energy consumption. A further (post-AM) finish machining operation is also needed. The masses of support structures and machining allowance could be supposed equal to 20% and 10% of the additively manufactured component, respectively.

- For the machining-based approach, the mass of the chips are removed under both raw (85%) and finish cutting (15%) conditions. All the life cycle inventory data for component production are listed in Table 2. The specific electric energy consumption has been converted into primary energy demand where needed (with η = 0.34). The CO_2 emissions have been obtained by assuming a CES value of 0.16 kg/MJ. The lifespans of the EBM and milling machines can be left out of the boundaries of the study.

- **Use phase:** The application of the component both in a short- and a long-distance aircraft has been envisaged. Average values for energy and CO_2 savings achieved by light-weighting are equal to 150,000 or 200,000 MJ/kg and 10,200 or 13,600 kg/kg, respectively.

Table 2. Data for additive and subtractive manufacturing

Eco-Property	Min	Max
Energy demand for EBM, E_{AM} (MJ/kg)	176.5	520.6
CO_2 footprint for EBM, $CO_{2\ AM}$ (kg/kg)	9.6	28.3
Energy demand for raw machining, E_{RM} (MJ/kg)	2.28	2.52
CO_2 footprint for raw machining, $CO_{2\ RM}$ (kg/kg)	0.17	0.19
Energy demand for finish machining, E_{FM} (MJ/kg)	18.5	20.4
CO_2 footprint for finish machining, $CO_{2\ FM}$ (kg/kg)	1.39	1.53

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Questions

- **Question#1:** Schematize the life cycle of the product by highlighting each phase of life and/or unit process, detailing the material flows. Please identify the main drivers for energy consumption and carbon dioxide emissions. Please declare all the assumptions.
- **Question #2:** Propose a formula to compute the performance assessment metrics for both the manufacturing approaches, under cradle-to-grave system boundaries.
- **Question #3:** Compute, plot and compare the results by using a bar chart. Please highlight the contribution of each phase of life to the cradle-to-grave values, under both the best-case scenario and the worst-case scenario.
- **Question #4:** Please compute the light-weighting factor (k^*) for which the machining-based and the AM-based approaches demand the same primary energy or produce the same CO_2 emissions.

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