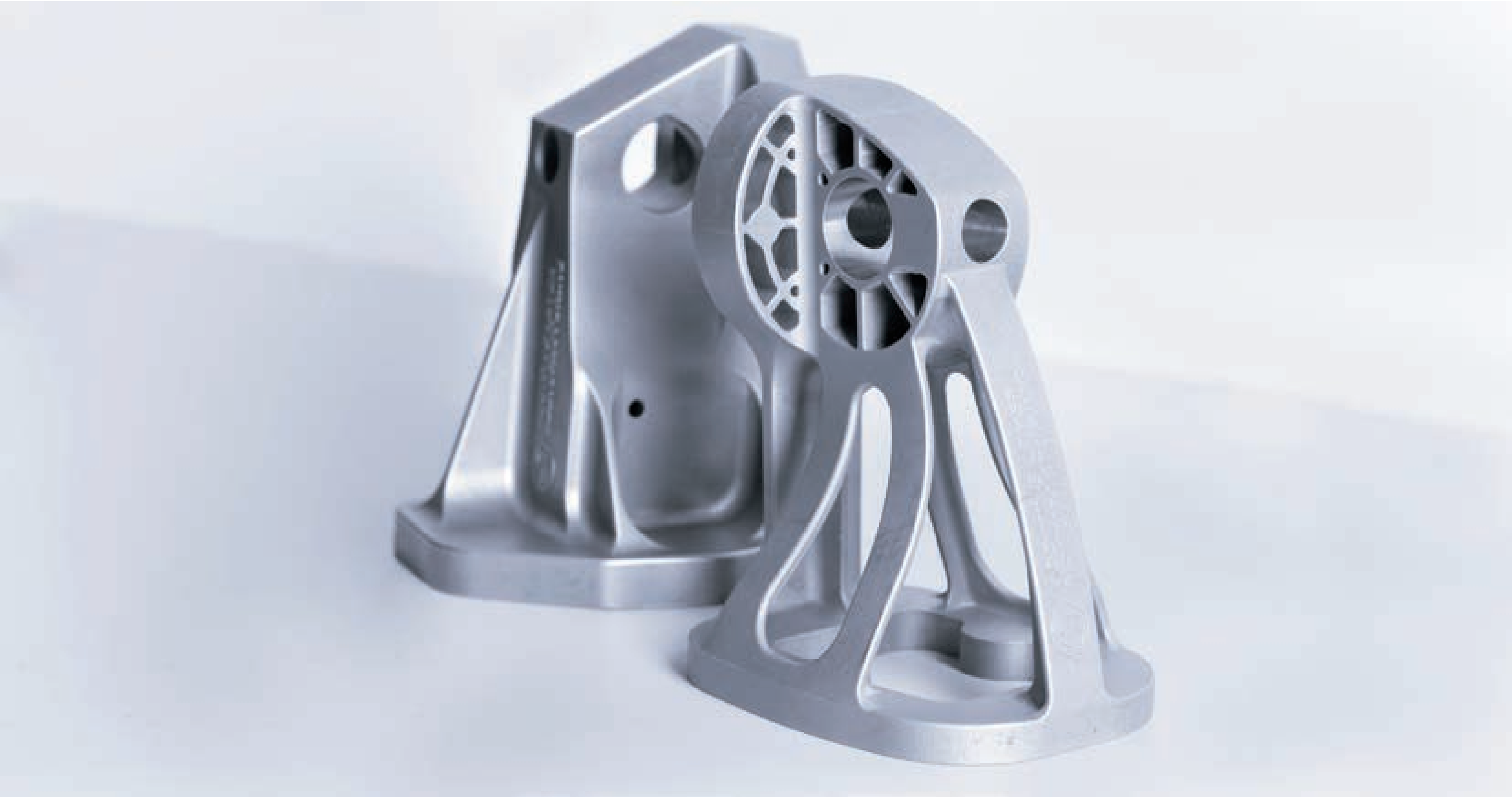
Whitepaper



Life Cycle Cooperation between EADS IW and EOS

e-Manufacturing Solutions

Life Cycle Cooperation between EADS IW and EOS

Enlarging knowledge around the eco-design of an aeronautic application by using the Additive Manufacturing (AM) technology.

Executive Summary

EADS is affected by the global impact of its manufacturing operations which can result in costs and externalities during the operational phase of its products but also during the manufacturing phase.

For this study, EADS as a customer and EOS as a technology supplier created a life cycle cooperation in order to gain a better understanding of the particular requirements and get an overview of the EOS technologies' readiness regarding sustainability and environmental criteria. The point of interest for this study has been an aerospace application (a bracket) using the AM technology.

As a first step, a conventionally manufactured application (in steel) was compared to an AM-manufactured one with optimized design (in titanium) by measuring the energy consumption over the whole life-cycle. For this application, the operational phase is typically one hundred times more important than the static phases over the life-cycle. By optimising the geometry and using titanium instead of steel, the EOS-AM produced application has the potential to lower the energetic impact during the use phase by almost forty per cent.

For the next step the 'static phases' were the point of interest. The manufacturing process was compared for the EADS application in titanium with optimized design, built with rapid investment casting and with an EOS platform. The energy consumption for the production of the bracket, including raw material production, manufacturing process and end-of-life is slightly smaller when moving from rapid investment casting to the EOS platform. This is due mostly due to the difference between the buy-to-fly ratios (b/f) of the different processes benchmarked, the greater amount of energy consumed during the manufacturing process and the respective heat treatments induced. As a next step, it will be necessary to better understand possible saving potential during the static phases of the life-cycle, by using the EOS technology with other different applications.

Introduction

Life cycle considerations are becoming increasingly important due to the need to consider sustainability – economy, quality and environment – in industry. But where a machine supplier or a material provider would traditionally conduct this type of analysis on their own, we wanted to develop a new approach clustering the different protagonists involved in the life cycle of one product in order to produce a single combined study. Indeed, in a global system, it seems to be of significant importance to understand the interdependencies between actors in terms of environmental impact and therefore potential environmental costs. With this study we would like to present a new form of cooperation – a so called "Life Cycle cooperation".

In addition to the generation of results, at the core of this joint study has been the process of integrating two different methodologies based on the same manufacturing process, in order to create a common holistic approach with shared objectives and a joint working process to follow. Thus, we assessed the relevance of a Life Cycle Cooperation at the research and development stage.

Conventional design of the steel cast bracket assessed at the upper left and topology-optimized design of the titanium AM-made bracket on the lower right corner.

Figure 1: The bracket used as the object of study at EADS IW. Source: EADS IW

This case study deals with the manufacturing of a bracket, EADS application on an EOS platform visible in Figure 1 above, in order to perform a vertical integration of the supply chain in a life cycle assessment.

1. Two individual studies: an uncompleted approach

EADS IW and an eco-design approach

EADS (European Aeronautic Defence and Space Company) is a global leader in aerospace, defence and related services. EADS vision 2020, in line with the Advisory Council for Aeronautics Research in Europe (ACARE) 2020 and Flight path 2050 objectives, is about ensuring that the group is ready for the challenges of the XXIst century, including sustainability. In engineering, this includes the development of an eco-design approach in order to influence design and manufacturing choices (quality, cost and environment) taking into account the overall life cycle of EADS products, from cradle to gatee.

EADS is a global leader in aerospace, defence and related services. In 2012, the Group – comprising Airbus, Astrium, Cassidian and Eurocopter – generated revenues of € 56.5 billion and employed a workforce of over 140,000.

EADS Innovation Works (IW), the corporate research centre of EADS, worked[1] on the application of a new set of Technology Readiness Level (TRL) criteria based upon sustainability and environment for the aeronautic sector, created by Airbus. Indeed, according to the NASA concept developed in the early 90s, Research and Technology (R&T) for aerospace goes through a nine-step process of TRLs, before a technology is fully validated in service. For each TRL review, the evolution in maturity of the technology is checked against defined criteria in order to evaluate feasibility and justification for continued investment.

A result of the collaborative worked carried out by EADS IW and Airbus is that the maturity level of the technology is now also evaluated from a sustainability/environment perspective. This new set of criteria assesses the environmental impacts of the technology at early research stages, enabling an eco-design approach of the application. Then, we need to ensure that a plan is in place to improve the 'sustainability performance' of the application developed through the subsequent TRL levels.

EADS IW understood the challenges of a sustainable strategy by focusing its R&T on the development of a new set of technologies that would improve the overall efficiency of future EADS products throughout their life cycle.

Additive Manufacturing (AM) processes have been utilized in the EADS organization for over a decade in polymers, but recently the technology has also seen significant progress in the processing of metals. The main drivers for adoption of these metallic processing technologies within EADS is the potential for reduced material waste in the manufacturing phase, coupled with geometric freedom that can allow for improved structural optimization – reducing the weight of the resulting parts and improving the environmental performance during the use phase. For these reasons, the technology is an interesting candidate for an assessment following a scientific approach.

[1] Project funded by the Technology Strategy Board (TSB) from 2009 to 2012.

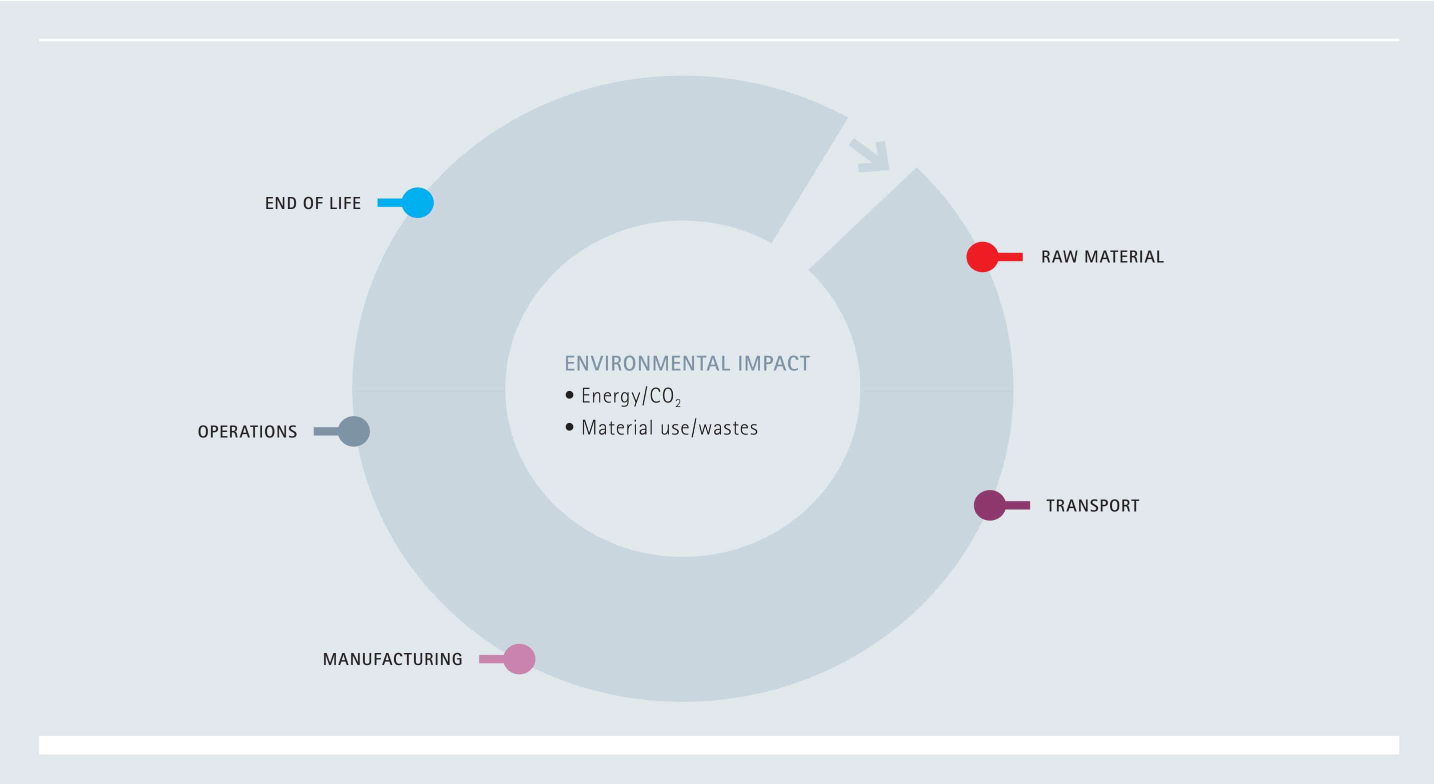


Figure 2: Brief description of the system assessed in the first study of the bracket made by EADS IW. Source: EADS IW

The methodology used is adapted from the Airbus streamlined life cycle assessment (SLCA) method, adapted from the ISO 14040 series. The assessment focuses on five phases of the life cycle: raw material extraction and production, transport, manufacturing and assembly, usage and finally end-of-life. Along with these life-cycle phases, metrics provide results in terms of environmental impact. What follows below are the main results of an initial study comparing the AM Direct Metal Laser Sintering (DMLS) process to a realistic casting candidate.

In this framework, and as part of the deliverables of a Technology Strategy Board (TSB) funded project, an SLCA was conducted on a generic bracket benchmarking the AM/EOSINT DMLS process with a conventional casting process used as the conventional baseline. The relative design freedom of the EOS process allowed the optimization of the design of the bracket via an iterative Finite Element analysis.

For this application, the AM/EOSINT DMLS technology using titanium for an optimized design of the bracket leads to interesting results in terms of environmental impact, compared to the conventional steel sand casting process with a conventional design, including the following:

- It uses less raw material thanks to the optimization of its design. The technology produces a net-shape part and generates less waste compared to the steel sand casting process; the overall buy-to-fly ratio is therefore improved. This leads to a 10 kg weight reduction per aircraft, equivalent to significant cost savings in fuel consumption and carbon taxation over the life of the aircraft.
- Figure 3 below shows the energy use over the overall life cycle (left hand side of the figure) or only during their static phases (right hand side of the figure). The scale on the left hand chart is 100 times higher than the one on the right hand chart which shows how important the operational phase is when compared to all the other phases of the life cycle. During the static phases, the AM/EOSINT DMLS M 270-based process consumes more energy than steel sand casting as one can see below on the right chart in Figure 3.

- More energy is used to produce the part as production of a titanium part is quite energy intensive – as is the EOSINT DMLS process itself – because of heat losses during the sintering process and the cooling system installed to buffer them. Moreover, the use phase has by far the biggest impact in terms of energy consumption and CO_2 emissions over the whole life cycle of the bracket (see the left chart of the figure 3 above). Therefore the increase in energy consumed and indirect CO_2 emitted by the static phases is negligible when compared to the benefit induced by a weight saving that results from an optimized design, which is enabled by the design freedom offered by the DMLS process.
- In terms of CO_2 emissions, the results comparing both processes are similar to the energy results displayed in Figure 3 above. As no CO_2 is emitted on site according to our model (only electrical powered devices used along the manufacturing process), these are the indirect emissions or more precisely, the emissions produced off-site in the energy plant to produce the electricity used on-site.
- There is a potential recycling issue around the support powder, still considered a hazardous material. By support powder, we mean the powder sintered during the process but not part of the component.

The energy consumed during the operational phase of the bracket, on the left hand side of the figure, is about a 100 times larger than the energy consumed through the static phase, insignificant on the left hand side of the figure but which is better described on the right hand side of this figure. Thus, optimization of the design has a direct effect on the operational phase's environmental impact.

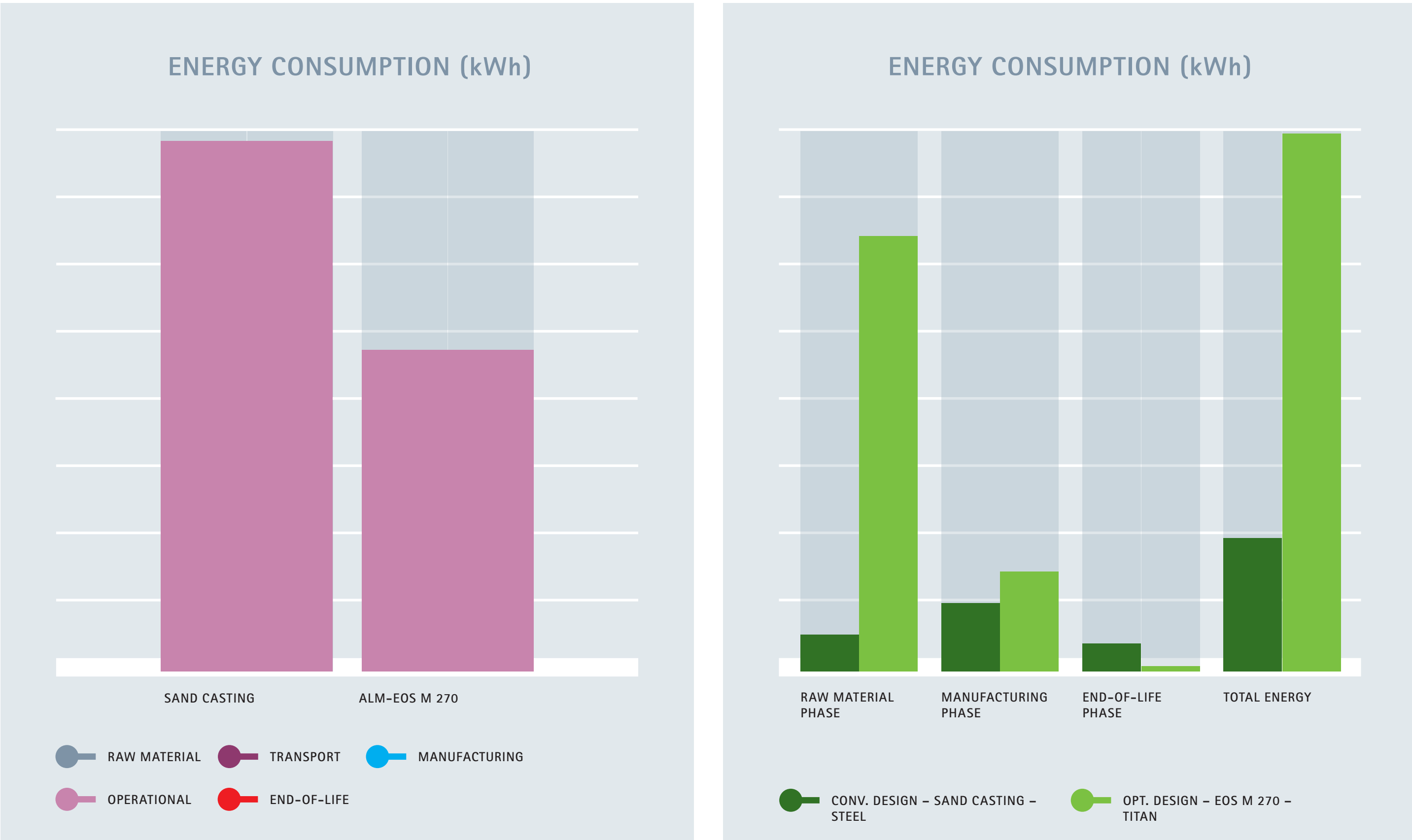


Figure 3: (left in kWh) Energy consumption of both processes through the overall life cycle of the bracket, (right in kWh) energy consumption through the static phases of the life cycle. Source: TSB funded project –EADS IW, 2009

As the first study was conducted from an industrial perspective, only the realistic combinations were examined. As a result, multiple variables were changed simultaneously between the casting process and the DMLS solution:

- Use of another technology
- Use of a different material (titanium instead of steel)
- Optimization of the geometry by using the net-shape possibilities of the DMLS technology

The first study used many variables between both options benchmarked and allowed us to assess, with a realistic case study, the importance of the operational phase. However, we could not assess the manufacturing phase in an isolated way using this method. Therefore, a subsequent study focused only on the strict change from one manufacturing process to the other in order to understand more precisely our future impact during this phase. Thus, this second study fixed two main variables: the material used is titanium and the design of the bracket is the optimized one.

Before starting a second and updated study, the next step was planned coming back to who created the platform: EOS. Explaining how it is used in aeronautic/aerospace, EADS IW asked EOS to assess the environmental performance of the manufacturing platform itself. It transpired that EOS had already performed a similar study coming from their own perspective, providing an excellent basis for comparison. The Life Cycle Cooperation (LCC) between EADS IW and EOS was to be born.

EOS and Product Carbon Footprint (PCF)

Founded in 1989 and headquartered in Germany, EOS is the technology and market leader for design-driven, integrated e-Manufacturing solutions for industrial applications. EOS offers a modular solution portfolio including AM systems, software and materials and their further development, services like maintenance, training as well as specific application consulting and support. As an Additive Manufacturing (AM) process the EOS technology allows the fast and flexible production of high-end parts at a repeatable industry level of quality. The technology paves the way for a paradigm shift in product design and manufacturing. It accelerates product development, offers freedom of design, optimizes part structures – also enabling lattice structures – and functional integration, and, as such, creates significant competitive advantages for its customers.

Sustainability issues are gaining more and more importance for businesses. For EOS, sustainability aspects have three different strategic implications:

1. Basis: to better understand the impact of the technology (material use, energy use, overall waste production) in the manufacturing process.
2. Knowledge: to build up knowledge about which applications built with the DMLS technology have the most relevant saving potential taking sustainability aspects into consideration (such as fuel/energy savings, material savings etc.).
3. Contribution to a sustainable development: to support users and customers of the DMLS technology with this knowledge to meet their own sustainability targets.

For the past two years, EOS has been working on the basis of this strategic approach. The Product Carbon Footprint (PCF) calculation of 1kg of laser-sintered material, carried out by EOS, supports this finding and lead to the creation of a database open to EOS customers, like EADS IW.

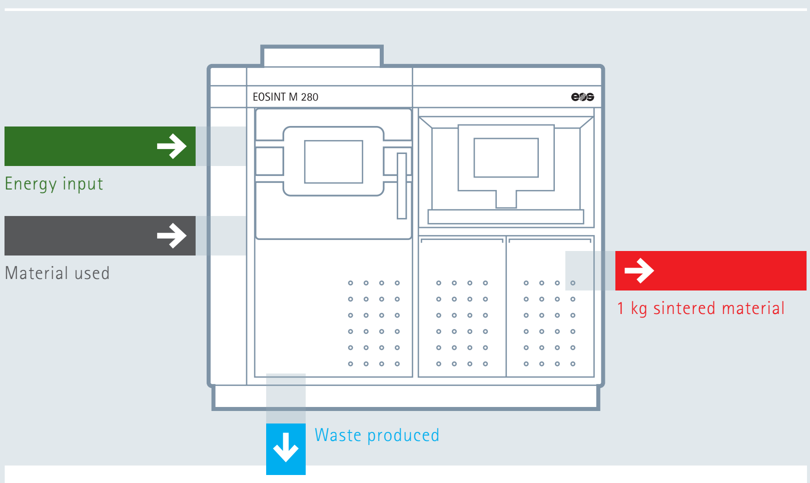
For this study the guidelines of the British PAS 2050[2] - defined by the British Standard Association – have been used. It helped in answering basic questions, for example about the system boundaries that were finally defined according to the cradle-to-gate approach. The use phase was excluded in this study as the PCF-database has been developed exemplarily for 1 kg of laser-sintered material, but not for a specific application. The assessment focused only on the early product life cycle phase stages such as raw material extraction and production, transportation and manufacturing. The result is given in kg CO_2 eq. emitted until the manufacturing phase of the component is completed.

[2] Publicly available specification.

As regards the data collection, EOS' own evaluations have been carried out with a thorough and relevant methodology, especially the energy use of the EOS systems and the peripheral devices in the manufacturing process itself. In other parts of the assessment it was necessary to revert to so-called secondary data, from external evaluations or databases.

The database now includes energy and CO_2 emission data for different materials used on different EOS-platforms.

This assessment identified that the manufacturing process itself seemed fairly energy intensive but without any comparison to other manufacturing



PCF Database (Manufacturing Process)	
Material: Metal	MS1 Ti64 SP2 Al
Material: Plastic	PA 2200 PrimePart DC
Systems	M 270 P 760

Figure 4: A Product Carbon Footprint (PCF), first approach by EOS[3]

processes. Also, the most important drivers for energy consumption along the value chain are mainly the production of raw

materials and the EOS platforms and their cooling systems. The results showed that the greatest potential for the reduction of energy consumption from CO_2-related emissions lies in the 'use phase' of a laser-sintered component.

As already mentioned, the identified biggest contribution to a sustainable development is only possible when working together closer with the EOS customers and users of the EOS technology. Only with a shared reflection, a wide understanding can be developed on which are those applications using the EOS-technology that contribute to a sustainable development and how big their contribution may be.

[3] Here the atomization of the powder was not initially taken into account within the boundaries of the PCF. This study was focused particularly on the manufacturing phase.

Thus, the next reasonable step was to use this database together with a customer in order to calculate the energetic input and the CO_2 emissions for a concrete application. EADS IW and its first environmental assessment carried out internally was obviously an interesting one.

	EADS IW	EOS
Study	Streamlined Life Cycle Assessment (SLCA)	Product Carbon Footprint (PCF)
Focus	**Life cycle assessment** Material use, waste production, energy consumption, CO_2 emissions	**Technology assessment** CO_2 emissions, energy consumption
Life cycle phases assessed	Raw material, transport, manufacturing, operational, end-of-life	Raw material, transport, manufacturing
Basis	Streamlined LCA (adapted from ISO14040 standard)	PAS 2050
System used	**EOSINT M 270**	
Outcome manufacturing	• Energy consumption per unit of weight laser-sintered material is high compared to other technologies, due to heat losses • Need for more reliable data sources in order to make a more robust environmental assessment • The support structure is a potential issue as a hazardous material	• The process appears to be fairly energy intensive but needs to be benchmarked • Energy consumption depends on the geometry and a certain number of parameters • The cooling system may have a higher impact than the system itself. • Powder atomization and argon consumption should be more thoroughly assessed
Outcome use phase	• AM/DMLS can lead to topology optimization which may induce important weight saving for an aircraft • Use phase has the biggest impact for an aircraft component	• The important need to have a design approach • Use phase needed to be assessed jointly with a customer

Figure 5: Overview of the methodologies used for both initial studies[4]

[4] It has to be taken into account that the information on both EOS and EADS IW side were not available to each other at this time when the project of life cycle cooperation was not even forecasted.

The decision to combine both results for a more objective life cycle approach

EADS and EOS both came to the same conclusion:
It is necessary to enlarge the scope of the work done separately beforehand. As we can see in Figure 5 above, the studies conducted where based on different methodologies, started from a different perspective and had different types of outputs. While EOS focused on the manufacturing phase, EADS IW chose a holistic method, assessing as much as possible of the overall life cycle of the bracket, "from cradle to gate". We understand how the EOS outputs can feed the EADS IW model, increasing the accuracy and relevance of the study, above all, during the manufacturing phase; here is the main purpose of the life cycle cooperation.

2. Creation of a Life Cycle Cooperation: a joint study between EADS IW and EOS

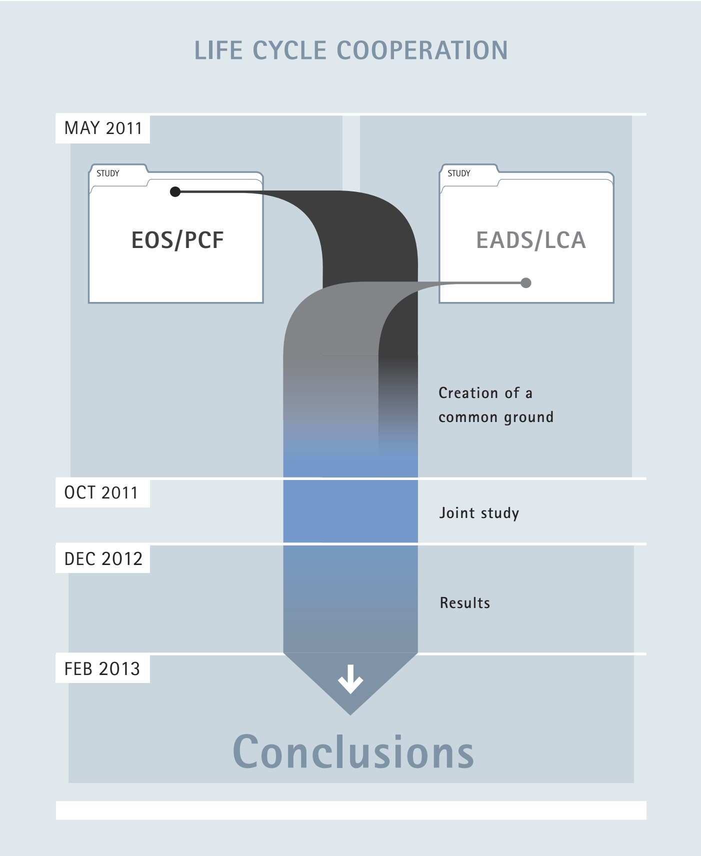


Figure 6: The chronological steps of the life cycle cooperation

The cooperation partners were well aware of the fact that they would not be able to create separate studies with the same quality as if they did a joint one. EOS was concentrating specifically on the manufacturing phase where EADS IW has been focusing on the extended picture of the life cycle for an aeronautic application. However, EADS IW had to work on the manufacturing phase with a low level of uncertainty as regards to the DMLS process – cf. Figure 7 below – if we compare it to a sand casting baseline.

This assessment applies a methodology adapted from Airbus and the so-called pedigree matrix uncertainty assessment (Weidema & Wesnaes, 1996). The result represents a weighted uncertainty based upon the energy consumed by each step processed, where 0 is the best and 1 is the worst in terms of data uncertainty.

Manufacturing phase assessed	Uncertainty value (the closest to 0 is the most reliable))
Steel – sand casting – conventional design	0.16
Titanium – DMLS by using EOSINT M 270 – optimized design	0.42

Figure 7: Weighted uncertainty of the manufacturing phases for processes within the first study. Source: EADS IW

The motivation for a joint study came from the good results of both the EADS IW and EOS studies, but also from clearly being aware of their limitations, as is usually the case in environmental assessment whatever the field of industry in which the assessment is performed. None of the studies were able to give an overview over the complete life cycle of the application with a relevant data quality. Moreover, there was a need to harmonize the different technologies compared within the same SLCA.

Baseline of a life cycle cooperation: an important communication phase

It was the approach of the EOS PCF project to provide a database in order to be used by customers to elaborate their own PCF for specific applications. EADS IW had already defined an application – the bracket shown in the previous chapter – for its LCA approach. Thus the bracket was chosen to be at the focal point of the joint study too.

Objectives

The following objectives were defined for the joint study:

1. Adapt and consolidate the LCA done by EADS IW for a bracket in order to set up a baseline regarding the sustainable performances of the AM EOSINT M 270 technology. This was to be done gathering EADS IW and EOS environmental assessments within a joint study with carefully defined boundaries
2. Compare the AM – EOSINT M 270 technology to a relevant technology which would be, in this particular case, rapid investment casting. The part produced would need to be made of the same material, Ti64, and have an optimized shape. Therefore this study would only assess the EOSINT DMLS process as a manufacturing process;
3. From the first results of the baseline for this new study, both companies would assess if any potential development would lead to an improvement in the sustainable performances of the technology. For the chosen case study, the objective was to see if by moving to the EOS next generation platform, the EOSINT M 280, the environmental drivers for the DMLS technology would improve.

This is a case study scenario that enabled EADS IW and EOS to assess the static phase with the best mark as regards the uncertainty of the data used.

Methodology

For this specific SLCA done by EADS IW, three static phases of the life cycle were included: raw material, manufacturing and end-of-life phases. Indeed, the dynamic phases were taken out of the scope for this second part of the study because:

- the transport phase assessed in the first part of the study was not significant compared to the other phases
- the operational phase was exactly the same for both manufacturing options benchmarked because the design of the bracket did not change in this second study, contrary to the first one. Also, both EADS IW and EOS understood fairly clearly that the operational phase has an impact about a 100 times higher than the other phases as regards emissions and energy consumption.

Furthermore, a PCF study takes into account energy consumption and CO_2 emissions, while an LCA considers the whole environmental impact, including as well the use of materials for example. To ensure the widest perspective possible, a methodology inspired from the Airbus SLCA methodology was chosen as the joint study.

Within these phases of the life cycle, the study partners decided to focus on the following aspects:

- Use of material (primary, secondary and tooling) and waste production
- Energy consumption/CO_2 emissions

For this new common study it was essentially important to ensure again the quality of the data used. The pedigree matrix was used again in this case.

Developments performed for the joint SLCA of a Ti bracket

Consolidation of the LCA exercise using the EOSINT M 270

To consolidate the SLCA, the two existing studies had to be introduced to both cooperation partners in order to create a common understanding for the methodologies and calculations used. A simplified data matrix based on LCA calculations was the basis to assess the technical gaps in the LCA as it can be observed below in Figure 8.

The data matrix was defined as the next step in order to give an overview of the existing data from both studies and their quality.

"EADS" in this figure above means a joint dataset between an Airbus property database and EADS IW internal dataset. Only the raw material, manufacturing and end-of-life phases (or static phases for an aircraft application) were taken into account in this study, for the reasons explained in the previous chapter.

From the tools available at EADS, made by Airbus, the uncertainty assessment tool was used for the manufacturing phase step processes providing a weighted uncertainty based on the energy consumption. The primary, secondary material and tooling (for mold and base plate) were included in the study.

This matrix clearly showed that the existing data from EOS and EADS IW with a view to the manufacturing phase were valid enough in terms of quality and completeness, but needed to be harmonized in order to consolidate a streamlined life cycle assessment and to reinforce the overall uncertainty of the joint dataset. It turned out that there were gaps in the raw material and the end of life phases. These gaps could not be filled either by EOS or EADS IW, as both sides could only make assumptions as to the relevant process steps in powder production. In order to gather reliable data, another protagonist involved the life cycle was included in the team, a material supplier which is in this case a powder supplier.

A supplier of titanium powder was ready to support the study with their know-how and data concerning the energy consumption for raw material production. Another external source of information was used in order to include the titanium rapid investment casting in the joint study and provide robustness to model in terms of uncertainty.

To fill the remaining gaps for the material production, the titanium powder supplier described the steps that need to be achieved in order to produce a titanium powder end product from the solid titanium material:

- Sources of raw material and transportation
- Energy consumption for the atomization process
- Yield of the atomization process and overall waste produced

The energy consumption of the relevant process steps were measured for all the relevant steps in order to have a total number of energy inputs and CO_2 emissions for 1 kg of titanium powder.

	Raw material	Transport	Manufacturing	Use phase	End-of-life
Energy/CO_2	EADS	EADS	EADS/EOS	EADS	EADS
Material	EADS	EADS	EADS/EOS	EADS	EADS

Figure 8: Overview of the data matrix for the life cycle of the bracket as regards the different processes assessed.

Also, in order to meet the requirements of the LCA assessment, the EADS IW data had to match with the EOS PCF data for the manufacturing phase.

The different scenarios approached were harmonized as far as possible in order to ensure that the only variable would be the manufacturing phase and its core technology used. The contact made by EADS IW for the conventional process is an important provider of rapid investment cast parts.

	Conventional process	EOSINT M 270	EOSINT M 280
Technology	Rapid investment casting	DMLS	DMLS
Source of data	EADS IW network	EOS	EOS
Raw material	EOS Ti64	Ti64	Ti64
Geometry	optimized	optimized	optimized

Figure 9: Overview of the scenario used for the study. Source: EADS IW

This part of the joint study – the creation of the life cycle cooperation – was a core process. The first important step was to agree on the application and the methodology as a baseline for the study. The attention on this process was of course a basis for the subsequent joint study, but also a process of creating a common ground of trust and willingness to cooperate. In creating a common understanding, EOS and EADS IW could specify common objectives for this study.

The third important aspect was to include other suppliers in the cooperation, such as the powder supplier and an external company controlling the rapid investment casting technology. They provided the know-how and the data input in terms of energy and material consumption that neither EADS IW nor EOS could contribute from their side.

Assessment of the new platform: the EOSINT M 280 DMLS

A new platform performing the DMLS process for metallic applications, the EOSINT M 280, was released by EOS in 2011. This platform presents improvements made on different aspects of the manufacturing process compared to the previous model made by EOS, the EOSINT M 270. One of the main improvements is the reduction by 50 per cent of the laser-sintering time compared to the EOSINT M 270 platform due to an increase of 100 per cent in laser power. This improvement induced changes in terms of the technologie's environmental footprint and as such was interesting to assess.

The study partners decided to benchmark the EOSINT M 280 with the EOSINT M 270 in terms of their environmental impact, updating also the first study made by EADS IW. The argon consumption and its impact were, as an example, not taken into account in the first study and this important parameter of the laser-sintering process was included in this second study. An important idea here is the 'gradual improvement' of processes, a concept connected to the ISO 9001 standard baseline concept.

To assess the potential improvements of the new machine platform EOSINT M 280, it was necessary to measure the energy consumption and other parameters during the manufacturing process.

The optimized bracket was then built on the EOSINT M 280 platform. Thus the energy consumption of the system itself and of the peripheral devices – such as chiller, compressed air – could be measured just as on the EOSINT M 270. Measurements of the post processes were done by EADS IW and with the help of an internal database. This provided an overview of the benefits offered by the DMLS process across two generations of machines and the improvements that could be achieved during further development of this system series in order to meet all the requirements of a complete "Green Tech".

3. Results of the environmental assessment through two generations of EOS platform

Resource use and waste production

Resource use and waste production are definitely interesting aspects to take into account. For some specific scarce materials, most of all in aeronautic and aerospace applications, it is likely to become an important driver for any decision-making process in the future. Here, the resource use is assessed for primary and secondary materials. The waste produced is also assessed, leading to the calculation of the standard buy-to-fly ratio, which shows the efficiency of resources use during the manufacturing process.

Consumption of resources by each manufacturing process

Both study partners decided to compare the three different processes using a ratio, combining the weight of (primary or secondary) raw material used during the manufacturing process to the embodied energy per unit of this raw material. In this way, rather than providing only absolute figures of weight of different materials, this took into account in one ratio not only the amount of raw material but also part of its intrinsic cost which is fairly well correlated to its embodied energy[5]. As an example, we cannot put a 1kg of titanium and 1 kg of argon gas on the same line of comparison.

The primary raw material includes only titanium without processing of the feedstock. Secondary raw material includes the tooling and also the cooling and inserting fluids used during the processes.

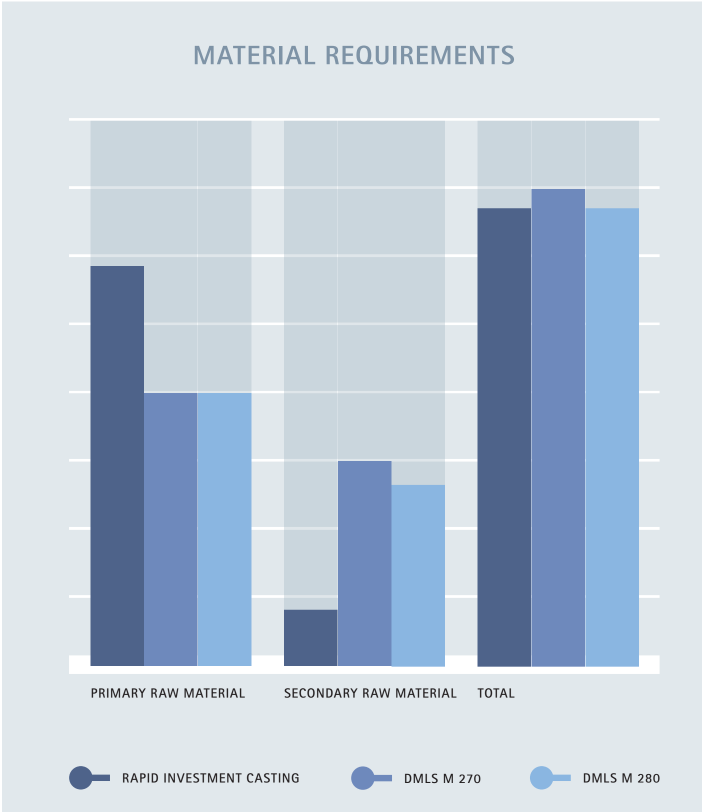


Figure 10: Resources used for the production of 1 bracket, weighted by their embodied energy within each manufacturing process (in kWh). Source: EADS IW

As regards primary raw material use, in Figure 10 above, there is a 28 per cent drop when switching to AM due to the efficiency of the DMLS process. The secondary raw material ratios showed an interesting benefit to the rapid investment casting option, with a ratio 78 and 73 per cent lower compared to the EOSINT M 270 and M 280 platform, mostly due to cooling and inerting argon shielding. This gas is used in significant quantities inside the building chamber of both DMLS platforms. However, it was possible to achieve an improvement of about 20 per cent in the reduction of this gaseous secondary raw material from the EOSINT M 270 platform to the M 280.

[5] Andrew McKillop, 2006 http://www.raisethehammer.org/article/438/peak_oil_and_commodity_pricing_fundamentals

Waste production of each manufacturing process

Like the resource use in the previous section, the mass of waste produced by each manufacturing process was weighted by the embodied energy of each waste in order to have a more objective layout comparing the different waste types together on the same plot. Below are the results of this assessment:

This way of presenting the results conveys a stronger and improved idea of the "embodied" cost of these material non-organic wastes for each alternative process that it was possible to recover by re-use or recycling. There are only two processes benchmarked here above as both EOSINT DMLS process lead to the same amount of waste produced.

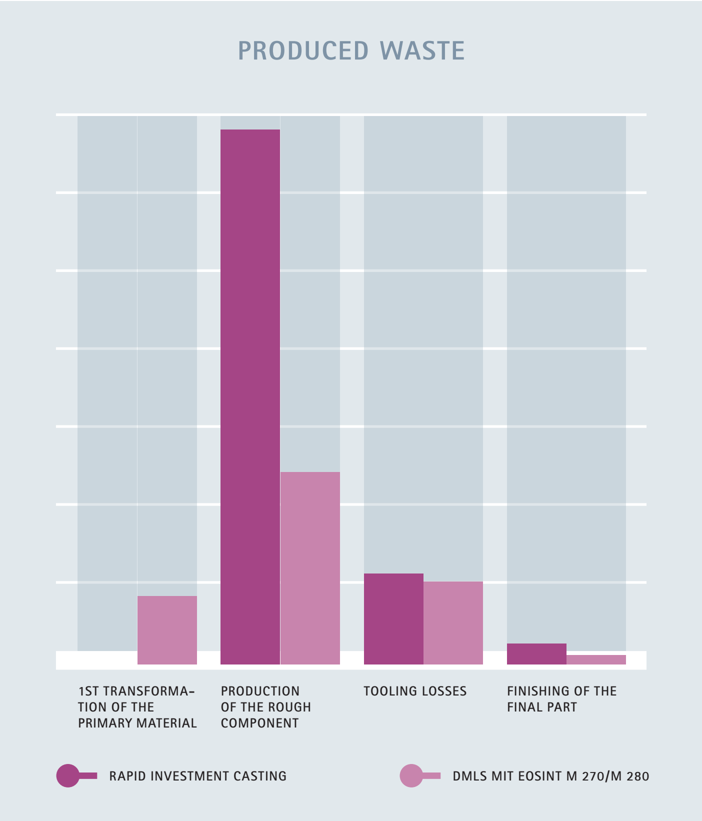


Figure 11: Waste produced weighted by its embodied energy for each process (in kWh). Source: EADS IW

On one hand, in Figure 11 above, the overall energy-weighted amount of waste produced during both DMLS processes is almost only half compared to the rapid investment casting alternative for the particular aeronautic bracket application. On the other hand, when measuring only the mass of waste produced between both options, there is a 91 per cent drop when switching to the DMLS process. Thus, the DMLS process is very promising in terms of waste management as compared to other alternatives. Moreover, the DMLS process induces only one type of waste material, here titanium for this application, rather than producing different types of waste which as a consequence need different methods of treatment.

In the case of the DMLS process, the production of the rough component induces the production of support structure waste, considered as a hazardous material. The support structure of the laser-sintered part is usually a mix of about 50 per cent of powder that could be used again and a thin walled structure of solid titanium. The dangerousness of the support structure only comes from its powder fraction. The latter is considered a hazardous material difficult to handle for health and safety reasons even if its use is broadly allowed. There is an obvious axis of improvement in sorting out these different fractions of waste in order to have only, as waste, the remaining solid fraction which is non-hazardous and valuable on the recycling market. Indeed, the powder could be re-used directly after its extraction from the support structure.

Comparison of the processes in terms of their buy-to-fly ratios (b/f)
A buy-to-fly ratio (b/f) provides the ratio between how much material needs to be purchased in order to manufacture the component and the flying part. This ratio reflects the efficiency of the manufacturing process in the use of primary raw material for the aerospace and aeronautic sectors.

Process	b/f
Rapid investment casting	2.1
EOSINT DMLS	1.5

Figure 12: Buy-to-fly ratios of both processes benchmarked for the manufacturing of a bracket. Source: EADS IW

Both manufacturing processes can be considered efficient compared to other alternatives such as machining where the b/f can be far higher.

However, the EOSINT DMLS process is more efficient than rapid investment casting in terms of titanium use for the reasons explained in the two previous sections (3.a.i and 3.a.ii). The improvements developed for the laser-sintering process are important as the latter offers ways to reduce the solid waste by sorting out the powder from the laser-sintered support structure fraction. Also, it is assumed that six parts can be nested each time on the same base plate, reducing the losses per part when the base plate is surface ground and re-used. Increasing the amount of parts nested through optimization of the surface footprint of the build can reduce the b/f ratio to a figure even closer to 1.

Energy consumption and CO_2 emissions

Overall energy consumption throughout the life cycle of the bracket
As regards the energy consumption of the three different options, the total energy used through the static phases is similar between the different process routes.

The end-of-life phase looks not significant compared to the other static phases. The raw material phase of DMLS processes is higher here compared to Figure 10 because here the atomization of the titanium powder is included in the plot.

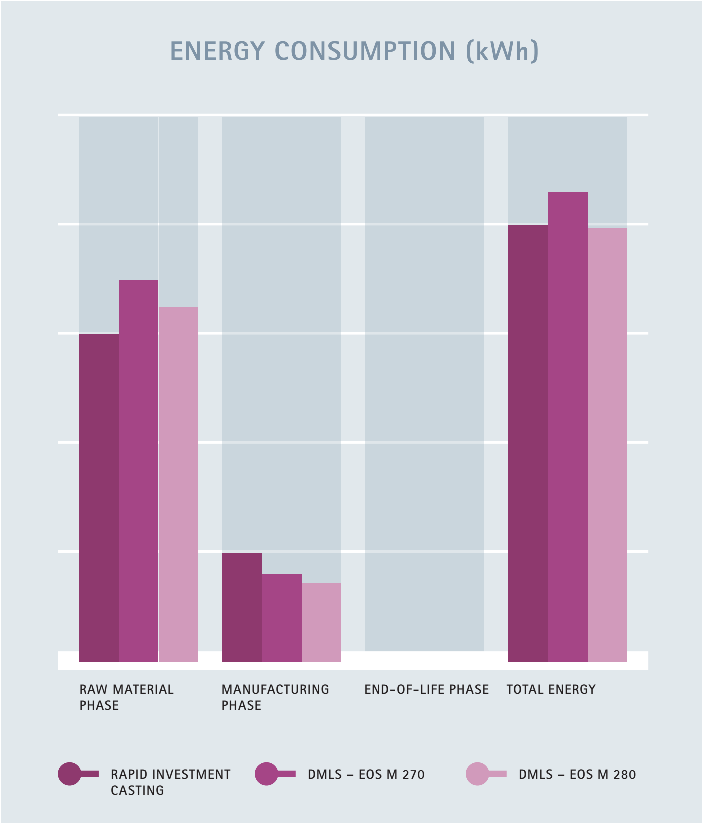


Figure 13: Energy consumption through the different static phases of the life cycle (in kWh). Source: EADS IW

Overall, the three processes benchmarked show similar energy levels even if the EOSINT M280 seems to show improvements compared to the other processes. The raw material phase of different processes is slightly different.

The higher use of titanium in the rapid investment casting case is set off in both DMLS processes by the atomization of the metal powder added to a higher use of secondary material, here argon, as seen previously in this paper. There is less argon needed for the manufacturing process on the EOSINT M 280 and thus the energy consumption embodied on the raw material phase of the later is lower compared to the EOSINT M 27.

A closer assessment of the manufacturing phase

Considering the manufacturing phase for the three options, the most significant differences between the three static phases can be observed.

As this phase is the main focus of this second study, it had a closer look at it. Below, an evaluation of the weighted uncertainty was conducted for the second study in order to assess the level of confidence in the results.

Both types of processes are pretty reliable as regards their overall weighted uncertainty value.

Manufacturing phase assessed	Uncertainty value (the closest to 0 is the most reliable)
Rapid investment casting	0.19
EOSINT/DMLS (EOSINT M 270 and M 280)	0.14

Figure 14: Weighted uncertainty of the manufacturing phases for processes within the second study. Source: EADS IW

The weighted uncertainty level of the three options is good as observed above in Figure 12. As both EOS processes are described with data coming from the database linked to the PCF made previously, the overall mark is higher on the EOS side than for the manufacturer providing the rapid investment casting option.

Now let's observe a detailed view of the energy consumption of each manufacturing option, per category of step processes. These categories are sorted out per type of step processes, equivalent but not equal between rapid investment casting and the DMLS processes.

The three categories of step processes account for a total of about 15 step processes that are not equally distributed.

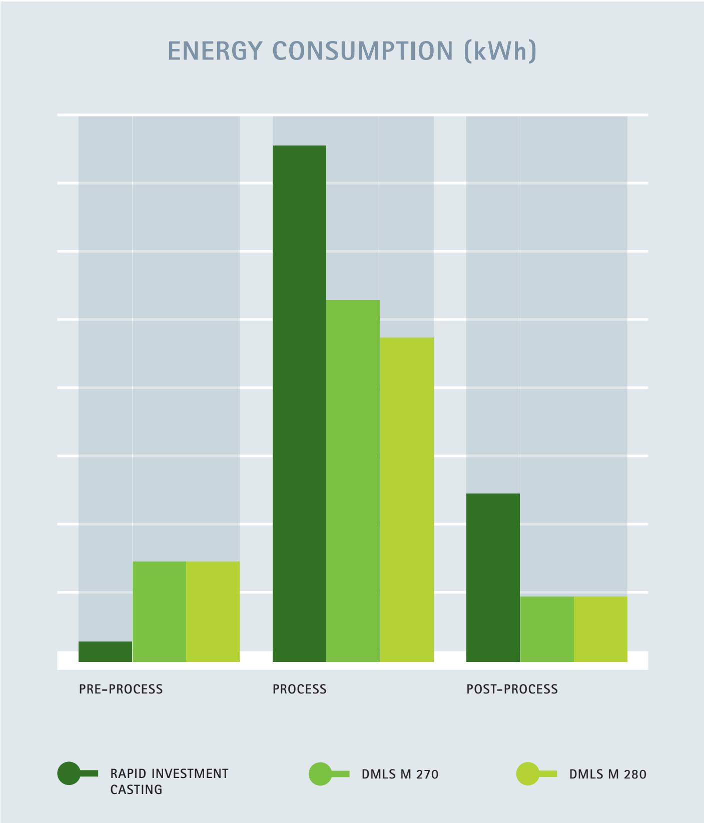


Figure 15: Take-down of the energy consumption for the different processes benchmarked during the manufacturing phase (in kWh). Source: EADS IW

The overall energy need of each manufacturing process is shown in Figure 13, in the global life cycle view. The pre-process phase is linked to the tooling preparation. During this process step, the milling of the titanium base plate for the EOSINT DMLS processes is quite significant in comparison to the production of the SLA epoxy model during the rapid investment casting.
In spite of the low energy needed during the tooling phase, the investment casting process is quite energy intensive compared to both EOSINT DMLS processes, with a small difference between these two laser-sintering processes, for the bracket application.

Another differential is to be observed during the various post-processes between casting and sintering manufacturing routes. The higher amount of energy involved in these steps for the casting process is mostly due to the machining phase with a five per cent loss in weight.

Despite the EOSINT M 280 platform seeming to be more energy intensive with a laser whose power doubled and a cooling system therefore consuming more energy as compared to the M 270 platform, its overall manufacturing energy bill is lower than the casting alternative. This is due to an important parameter which is the build time, reduced by a factor of more than two which gives the EOSINT M 280 platform an interesting improvement, with less energy needed by the cooling system.

A look at the CO_2 emissions

The air emissions are another important parameter, regarding current regulations such as the Kyoto Protocol. The Green House Gas (GHG) emissions include emissions of CO_2, CH4, N22O, HFCs, PCFs and SF6, here vizualised in a synthetic way by using the unit kilograms of carbon dioxide equivalent (kg CO_2 eq.), as presented in Figure 16 below.

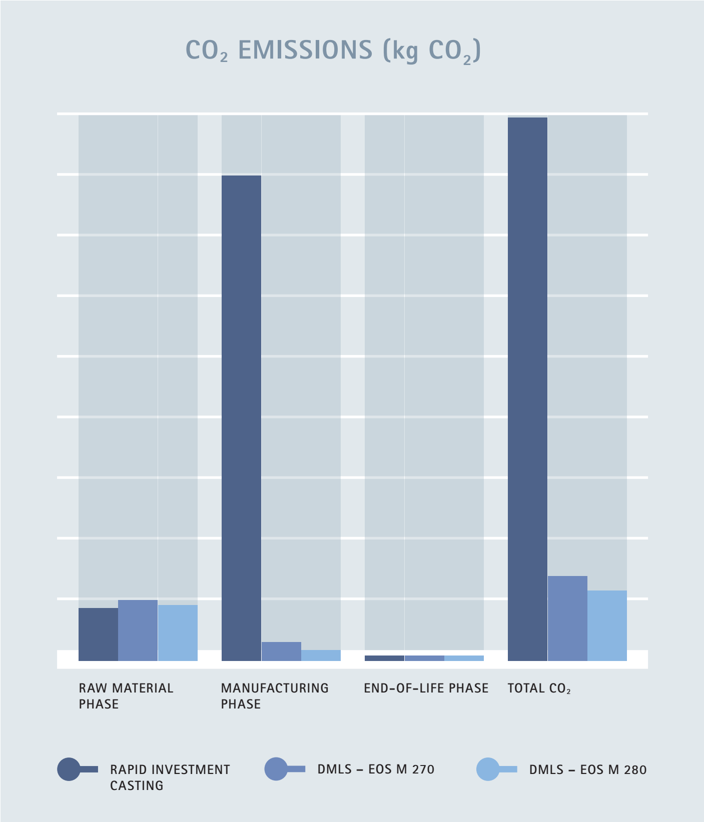


Figure 16: Emissions of carbon dioxide through the static phases of the different design options (in kg CO_2 eq.) Source: EADS IW

Most of the CO_2 emissions visualized in Figure 14 for the three options benchmarked come from indirect emissions as explained previously, linked to the off-site emissions at the power plant. Only during the manufacturing phase were some direct emissions generated in significant quantities in the case of the rapid investment casting. Indeed, the casting process needs a ceramic mold cured from an SLA epoxy pattern which is usually "flashed out" at a high temperature in a furnace. This process releases a significant amount of direct and indirect CO_2 emissions whereas in the case of the DMLS process, the emissions are indirect and come from electricity production.

It was possible to observe slight improvement between the EOSINT M 270 and M 280 platforms, resulting from the reduced amount of argon used during the manufacturing process and the improved energy efficiency of this phase, resulting in lower indirect GHG emissions.

All these results, from the use of material to the use of energy and release of GHG, give an interesting overview of the three options benchmarked, with interesting relative benefits observed on the DMLS process and more precisely, between both DMLS platforms.

Macro-analysis of the environmental assessment

As a second study, resulting from the life cycle cooperation between EADS IW and EOS, a streamlined life cycle assessment was performed comparing rapid investment casting to the EOSINT DMLS process with two different platforms, the M 270 and the M 280.

Raw material production has the biggest impact on energy consumption. This means the driver in terms of energy consumption and CO_2 emissions is the material and not the manufacturing process itself. Going a step further, the buy-to-fly ratio seems to be the most important parameter influencing the environmental impact during the static phases.

EADS IW and EOS also gathered knowledge as regards the embodied energy of different materials used during the manufacturing phase, both primary and secondary. DMLS is, as a result of this study, 30 per cent more efficient, assessed by the comparison of the b/f ratios.

With the raw material phase boundaries included, in this case the argon consumption, during the manufacturing process on the EOS platform, the importance of this secondary material in terms of embodied energy and an improvement has been assessed at this regard when moving from the EOSINT M 270 to the EOSINT M 280.

The energy consumption for the production of the bracket, including raw material production, manufacturing process and end-of-life is slightly smaller when moving from rapid investment casting to the EOS platform. This is due mostly to the difference between the b/f of the different processes benchmarked and more energy consumed during the manufacturing process. Comparing the two different DMLS platforms it turned out that the cooling system was the highest "well" of energy and therefore the focus point for further improvements. Indeed, the laser power is due to increase by the next generation in order to reduce the cycle time of the DMLS process.

The CO_2 emissions are also reduced when switching to either of the EOS processes, which are similar in this respect. The rapid investment casting is, in terms of production, as flexible as the DMLS process but needs the burning of an SLA epoxy model in a furnace which is a process producing a high amount of GHG.

EADS and EOS drew three main technical and strategic conclusions from this exercise.

First of the all, this study has shown how important it is to get a better understanding of titanium production. If the extraction and processing of the material has such a large impact from an energy perspective, then its price is likely to be volatile depending on the price of energy and any potential carbon tax on energy. The alignment of the supply chain is thus of high importance, as are R&D efforts in developing less energy intensive processes to extract titanium from titanium ore.

Secondly, one part of the life cycle has not been tackled sufficiently: the end-of-life phase. With increasing pressures on material supply, recycling is becoming a key factor. The results of this study have contributed to a better understanding and highlighting of this phase where improvements are expected to be performed within the coming years.

Finally, the cooperation between EADS IW with EOS and its titanium powder supplier has absolutely opened the door to a supply chain cycle approach, increasing awareness at EADS IW and EOS for the need to integrate all relevant players in the whole process. This 'life cycle approach' is key to industrial resilience.

The upper part of this drawing is a synthetic view of the bracket life cycle "from the cradle to the grave", used by EADS IW to assess the environmental impact of the bracket through its life cycle. The EOS approach only takes into account a part of this life cycle, "from the cradle to the gate" outside the company. The lower part describes the different features composing the life cycle cooperation.

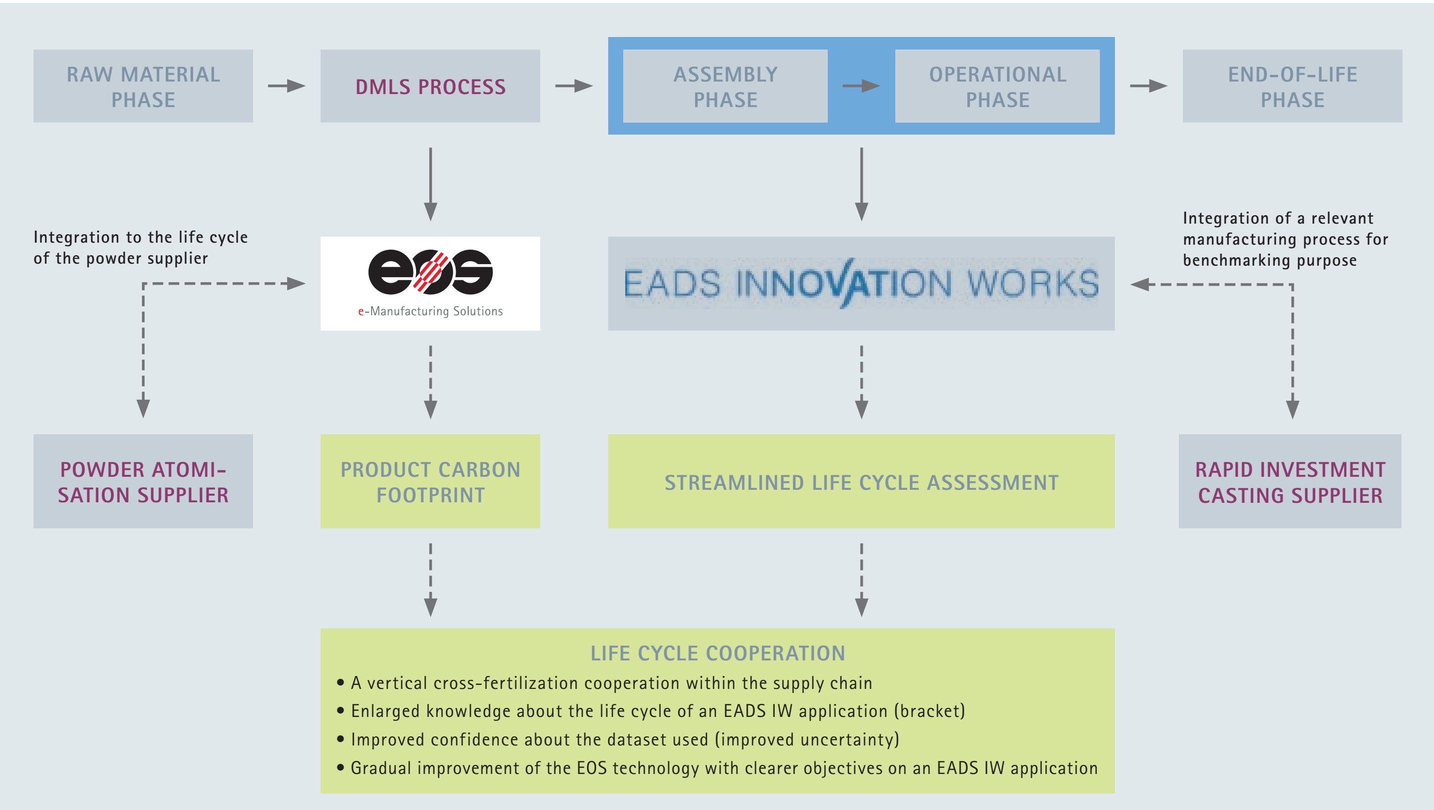


Figure 17: A life cycle cooperation approach by EADS IW and EOS on an aeronautic application

Conclusion

This study not only offers results in facts and figures, it also serves as the first real example of a vertical approach to the life cycle, too. It can sometimes be difficult to cooperate in industry for obvious reasons. The life cycle cooperation has been an attempt to integrate the supply chain further by sharing information between EOS, a developer of additive manufacturing processes and EADS IW.

The key to this success can be found in the early stages of the joint study. EOS and EADS IW spent a long time discussing and creating a baseline with remarkable conditions in order to combine their approaches.

We consider three steps to be crucial to the quality and success of our cooperation:

- **Creation of a quality data matrix:** with this matrix we gained an overview of the each other's know-how and database. An uncertainty assessment, a result of the strong internal cooperation within EADS between EADS IW and Airbus.
- **Building the team:** with the data matrix we were able to identify the gaps. In order to achieve overall data quality throughout the whole life cycle it was necessary to include a powder supplier with knowledge that neither of the other partners possessed.
- **A common understanding:** with our process to create a common ground we already gathered a better understanding of each other's objectives, motivations and the methodologies. Creating a document with the input and commitment of all cooperation partners was key to initiating a joint study.

This process fits well into the creative, effective and holistic framework all involved are trying to implement to tackle the challenges of sustainable manufacturing of eco-designed products. There is a need to keep the collaboration open from the earliest stage possible.

All partners involved agree that the initial objectives set at the beginning of the project were fulfilled but they only start a new trend of joint projects. The next step will be for EADS IW and EOS to work with other protagonists involved within the life cycle of relevant applications, and broaden this approach. The objective would be to assess from a baseline how each technical development at any stage would have an impact on the life cycle of the product, and more importantly, on the other parties involved. Hence, the results from the assessments would be even more reliable and the resilience of the industry value chain of the product would be strengthened. EADS is also committed to continuing the gathering of more knowledge around AM processes and additive layer manufactured applications, for further potential use in EADS products.

LCA is a key new approach to cluster industrial players not only with a single economical approach. It is about understanding how industry has to move towards the next great challenge of sustainability.

EOS GmbH
Electro Optical Systems
Corporate Headquarters
Robert-Stirling-Ring 1
82152 Krailling/Munich
Germany
Phone +49 89 893 36-0
Fax +49 89 893 36-285

Further EOS Offices

EOS France
Phone +33 437 49 76 76

EOS India
Phone +91 44 28 15 87 94

EOS Italy
Phone +39 02 33 40 16 59

EOS Korea
Phone +82 32 552 82 31

EOS Nordic & Baltic
Phone +46 31 760 46 40

EOS of North America
Phone +1 248 306 01 43

EOS Singapore
Phone +65 6430 05 50

EOS Greater China
Phone +86 21 602307 00

EOS UK
Phone +44 1926 62 31 07

www.eos.info • info@eos.info

Think the impossible. You can get it.

e-Manufacturing Solutions

Status 10/2013. Technical data subject to change without notice. EOS is certified according to ISO 9001.