Case Study

Exploring Sustainability in Additive Manufacturing

Developed and curated by the Ansys Academic Development Team

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Summary

This case study delves into examining the environmental impact of manufacturing an airplane bracket through conventional machining and Additive Manufacturing (AM). By comparing these methods, we aim to elucidate sustainability principles, emphasizing the importance of production processes, and design considerations in mitigating environmental impact. Through this exploration, we hope to provide educators and students with valuable insights to integrate sustainability concepts into engineering curricula, empowering students to address real-world challenges while promoting eco-friendly practices in manufacturing

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1. Introduction

In today's world, we're grappling with an urgent climate crisis, with rising temperatures, extreme weather events, and melting ice caps painting a grim picture of our planet's future. As the effects of climate change become more pronounced, there's a growing recognition of the need for industries like aviation to prioritize sustainability. In this context, our study delves into the environmental impact of manufacturing an airplane bracket, aiming to understand how different production methods, material choices and geometries can contribute to mitigating or exacerbating this global challenge. Through examination and comparison of conventional machining and Additive Manufacturing, we seek to uncover pathways toward more eco-friendly aircraft production, aligning technological advancements with the imperative to protect our environment for future generations.

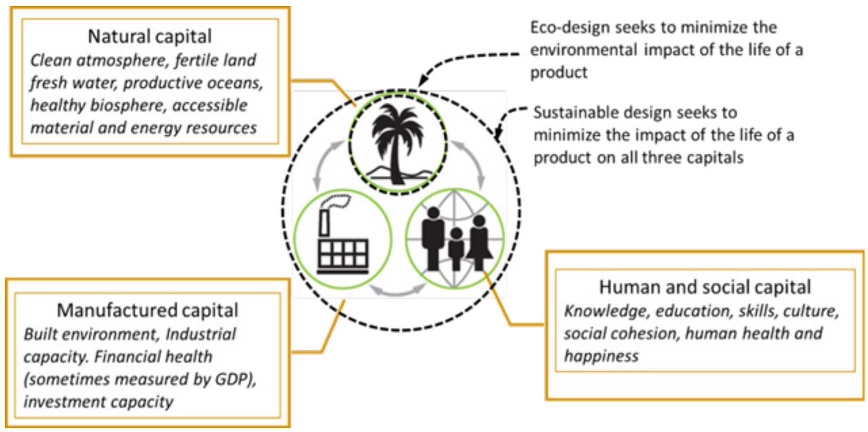


Figure 1 - The three-capital model [1] illustrates that the three main pillars underlying sustainability are: economic, social-cultural, and ecological. The figure also displays how eco-design and sustainable design differ in evaluating these capitals.

As we embark on this investigation, it's essential to acknowledge that sustainability encompasses not only environmental concerns but also considerations of economic viability and social equity. Sustainability efforts aim to balance the impact on three pillars: natural, manufactured, and social capitals, as shown in Figure 1. While our study primarily delves into the environmental implications of manufacturing processes for an airplane bracket, it's crucial to recognize the interconnectedness of these pillars. Our focus on environmental capital highlights the imperative to minimize carbon emissions, reduce waste generation, and conserve natural resources in manufacturing. However, we recognize the broader context in which sustainability operates, acknowledging the need for holistic approaches that address economic viability and social equity alongside environmental stewardship.

1.1. The Climate Crisis

The Intergovernmental Panel on Climate Change (IPCC), a leading authority on climate science, has outlined crucial benchmarks known as the 1.5°C and 2°C scenarios. These scenarios represent temperature thresholds relative to pre-industrial levels, beyond which the impacts of climate change are projected to intensify significantly. While these terms may be unfamiliar to some, they are pivotal markers in global climate discussions. Essentially, they signify the maximum allowable increase in global temperatures to prevent the most catastrophic consequences of climate change. Achieving these targets requires concerted efforts worldwide to reduce greenhouse gas emissions and transition to sustainable, low-carbon economies.

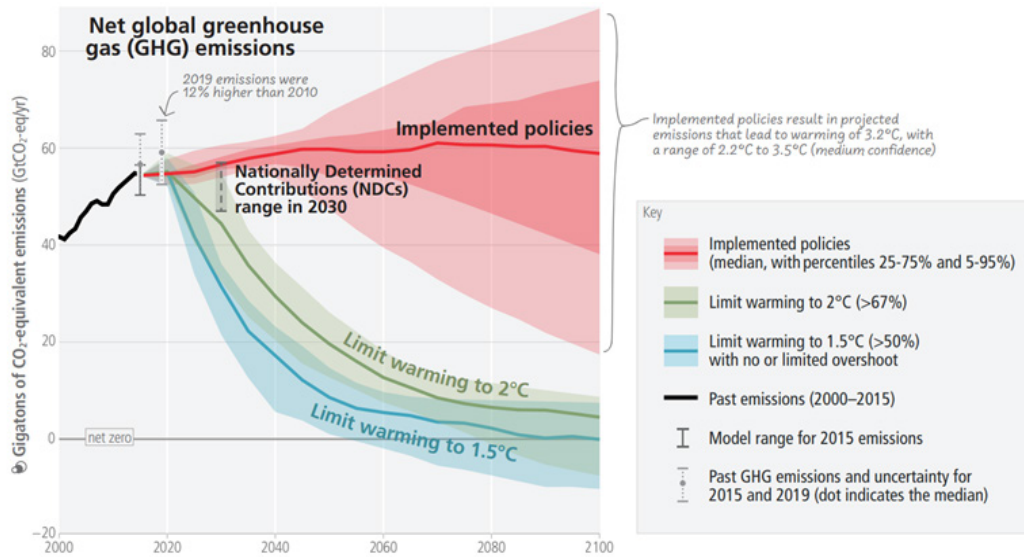


Figure 2 - Global emissions pathways consistent with implemented policies and mitigation strategies. The figure shows the development of global GHG emissions in modeled pathways. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020. Ranges of modeled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue and pathways that limit warming to 2°C (>67%) are shown in green. Global emission pathways that would limit warming to 1.5°C (>50%) with no or limited overshoot and reach net zero GHG in the second half of the century do so between 2070–2075. [2]

Efforts to limit global warming to 1.5°C or 2°C involve drastic reductions in greenhouse gas emissions, transitioning to renewable energy sources, enhancing energy efficiency, and implementing various adaptation measures to cope with unavoidable impacts. However, progress toward meeting these thresholds set by the IPCC has been mixed, as shown in Figure 2. Efforts to reduce greenhouse gas emissions have been underway, but the pace and scale of these efforts have not been sufficient to guarantee staying below these thresholds. Several factors contribute to this mixed progress, for example:

- Emission Reduction Efforts: Many countries have made commitments to reduce their greenhouse gas emissions, often as part of international agreements such as the Paris Agreement. However, the actual implementation and achievement of these targets vary, and some countries have struggled to meet their commitments.
- Challenges in Transitioning to Renewable Energy: While renewable energy sources such as solar and wind power have seen significant growth in recent years, fossil fuels still dominate global energy consumption. Transitioning to renewable energy at the necessary scale requires substantial investment, infrastructure development, and policy support.
- Economic and Political Factors: Economic interests, political priorities, and competing agendas can sometimes hinder progress toward emission reduction goals. Balancing the need for climate action with other societal priorities can be challenging for policymakers.

1.2. The environmental impact of the manufacturing sector

The manufacturing sector is a significant contributor to global carbon emissions. Although the exact proportion can vary (depending on factors such as the methodology used for calculation, the definition of the manufacturing sector, and the region being considered), it is estimated that the manufacturing and production sector accounts for one-fifth [3] of global carbon emissions and 54% [4] of the world's energy usage. It's, however, essential to note that this estimate includes both direct emissions from manufacturing processes (e.g., energy used in industrial processes, combustion of fossil fuels) and indirect emissions associated with electricity consumption.

Efforts to reduce carbon emissions from the manufacturing sector often focus on improving energy efficiency, adopting cleaner production technologies, increasing the use of renewable energy sources, and implementing carbon capture and storage (CCS) technologies where feasible. Continued efforts to decarbonize the manufacturing sector are crucial for achieving global climate goals and transitioning to a low-carbon economy. This requires collaboration among governments, industries, and other stakeholders to develop and implement effective policies, incentives, and technological solutions.
In this case study we will focus on whether additive manufacturing can be a part of the solution.

1.3. Unlocking the environmental benefits of Additive Manufacturing

Additive Manufacturing, also known as 3D printing, offers several environmental benefits compared to conventional or subtractive manufacturing methods. These advantages stem from the unique characteristics and processes involved in AM, which contribute to enhanced sustainability and resource efficiency. Below are four key environmental advantages of AM:

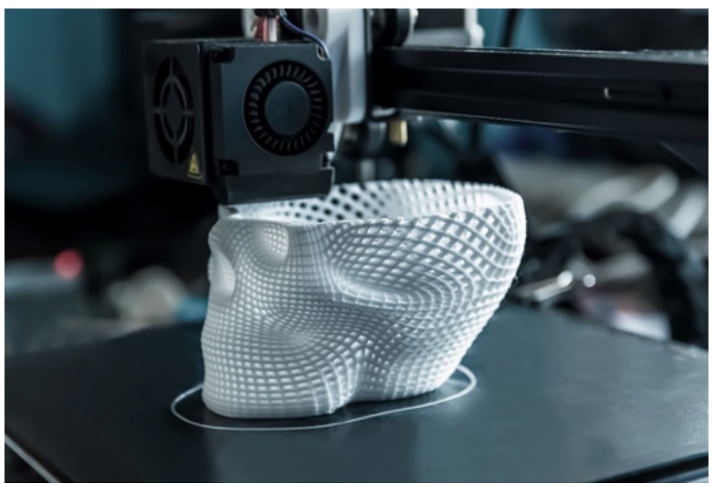


Figure 3 - Venturing into new horizons: A 3D printer meticulously crafts a white plastic skull model, inviting reflection on the sustainability of Additive Manufacturing (AM) by showcasing its capacity to reduce material waste.

1.3.1. Material Efficiency

One of the primary environmental benefits of AM is its superior material efficiency. Unlike traditional manufacturing methods that often involve subtracting material from a larger block or sheet, AM builds components layer by layer, precisely depositing material only where it is needed. This approach results in significant material savings and reduced waste generation. Additionally, AM enables lightweighting strategies, one of which is topology optimization, a computational design process that systematically removes excess material from a component's geometry while ensuring it maintains structural integrity and meets performance requirements, ultimately resulting in the most efficient use of material.
Topology optimization plays a pivotal role in enhancing the environmental impact of additively manufactured components by facilitating lightweighting, cost reduction, and minimizing material waste. Through topology optimization, engineers can leverage AM's freedom in design to create complex geometries that are optimized for specific performance criteria, such as strength and stiffness, while simultaneously minimizing material usage. This optimization process allows for the creation of

lightweight components that maintain structural integrity, leading to reduced material consumption and lower production costs. Moreover, by utilizing topology optimized geometries, AM can significantly reduce material waste compared to traditional manufacturing methods, where excess material is often discarded during machining or casting processes. Overall, the combination of topology optimization and AM offers a sustainable approach to manufacturing, promoting material efficiency, cost-effectiveness, and environmental responsibility.

1.3.2. Resource Efficiency

AM minimizes resource consumption and waste generation in several ways. Unlike conventional manufacturing processes that require specialized tooling for each component, AM eliminates the need for tooling altogether. This reduction in tooling not only saves resources but also reduces energy consumption associated with tool production and maintenance. Furthermore, AM can streamline supply chains by producing components on-demand, reducing the need for inventory storage and transportation, thereby decreasing carbon emissions associated with logistics.

1.3.3. Production Flexibility

Another environmental advantage of AM is its inherent production flexibility. Traditional manufacturing setups often require dedicated production lines for specific products, limiting flexibility and adaptability. In contrast, AM enables rapid product switching without the need for retooling or reconfiguring production lines. This flexibility allows manufacturers to respond quickly to changing market demands, optimize production schedules, and reduce downtime, ultimately resulting in resource and energy savings.

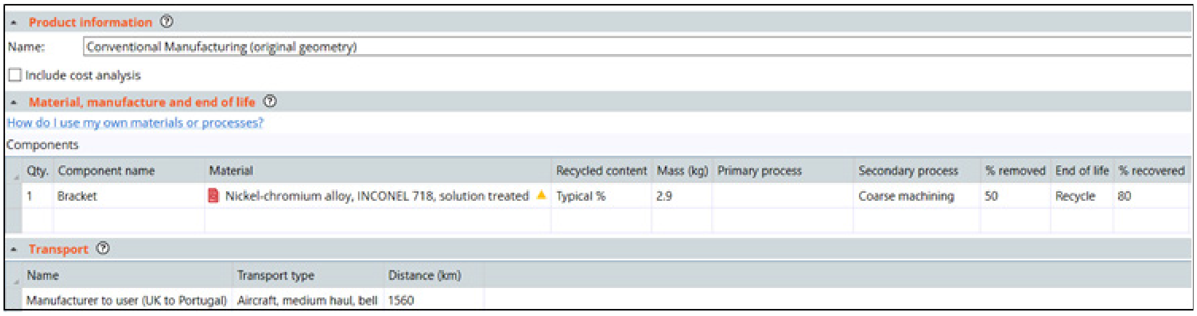
1.3.4. Part Flexibility

AM offers greater part flexibility compared to conventional manufacturing methods, contributing to improved environmental sustainability. Components manufactured using AM can be easily customized or modified to meet specific requirements, promoting repairability and extending product lifespans. Additionally, AM facilitates the consolidation of multiple parts into a single component, reducing the overall number of components needed and minimizing storage requirements. This consolidation not only saves material but also simplifies assembly processes, further enhancing resource efficiency.
In conclusion, Additive Manufacturing presents significant potential environmental advantages over conventional manufacturing methods. This, of course, does not mean that AM can always be the right choice. In some cases, AM processes can consume substantial energy or emit pollutants, potentially offsetting its environmental benefits. Additionally, AM may not be as advantageous for large-scale production or certain materials where recyclability is limited. We will explore this further by the end.

2. Eco-impact of manufacturing an aeronautical bracket

2.1. Conventional manufacturing of the bracket

Illustrated in Figure 6, the original geometrical design of the bracket serves the conventional manufacturing process, specifically machining. Utilizing Inconel 718 as the material, the component's total mass measures 2.9 kg. Employing the Eco Audit tool in Ansys Granta EduPack (Level 3 Aerospace database) allows for the assessment of the environmental impact associated with producing this bracket. The bill of materials and transportation requirements being used in this analysis is available in Figure 4.


Product information
Name: Conventional Manufacturing (original geometry)
Include cost analysis
Material, manufacture and end of life
How do I use my own materials or processes?
Components

Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	Secondary process	% removed	End of life	% recovered
1	Bracket	Nickel-chromium alloy, INCONEL 718, solution treated	Typical %	2.9		Coarse machining	50	Recycle	80

Transport

Name	Transport type	Distance (km)
Manufacturer to user (UK to Portugal)	Aircraft, medium haul, bell	1560

Figure 4 - Bill of materials and transportation needs being considered in Eco Audit for the first scenario in which conventional manufacturing is used to produce the original design of the bracket.

The Eco Audit tool offers insights into the Climate change (CO2-eq) and Energy requirements for manufacturing the bracket, detailed in Figure 5. Notably, while the Manufacturing phase is represented in this assessment (comprising 0.7% of total Energy and 0.7% of total Climate change), the Material phase dominates significantly (constituting 91.3% of total Energy and 91.5% of total Climate change). This dominance is influenced by the machining process employed, where a larger material block is machined to achieve the final geometry, leading to waste material generation. Furthermore, the bracket's substantial mass, dictated by its geometric design to facilitate conventional manufacturing, exacerbates the environmental impact.

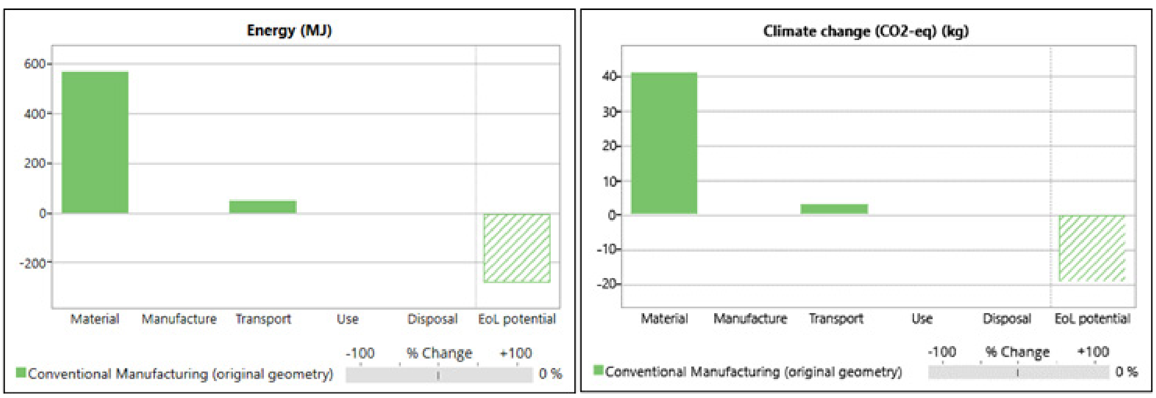


Figure 5 - Eco Audit summary charts displaying the environmental impact of the first scenario (conventional manufacturing of the original design of the bracket), namely the energy requirements (left panel) and Climate change (right panel).

2.2 Additive manufacturing of the bracket

As mentioned earlier, AM offers engineers the flexibility to innovate designs, capitalizing on the lightweighting advantages provided by topology optimization. To achieve this, Ansys Discovery can be utilized to optimize the original bracket geometry. The initial bracket design, depicted in Figure 6, features a fixed boundary condition at the bottom section of the bolt drilling, while an 8000N load is applied to the flap link, with force components distributed equally in the x- and y-directions (5660N and -5660N, respectively).

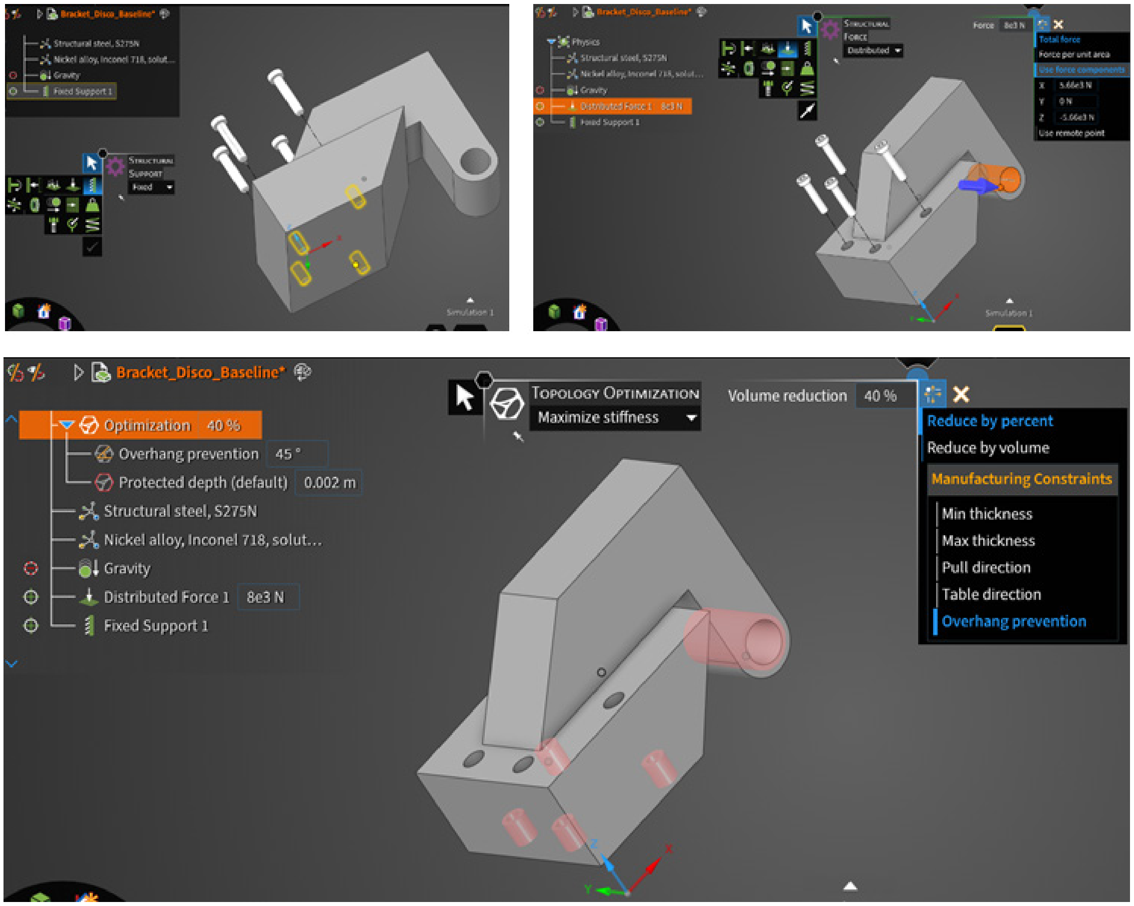


Figure 6 - Pre-processing setup, starting with the definition of the design domains for (a) the fixed boundary conditions and (b) the applied load components. Followed up by (c) setting up the Topology Optimization with an overhang prevention constraint set to 45° to maximize stiffness while reducing the bracket's weight by 40%. A protected depth around the boundary conditions and loading areas is automatically applied.

In this case study, we'll optimize the original bracket geometry to achieve specific objectives: maximizing stiffness while reducing the bracket's weight by 40% and applying an overhang prevention constraint set to 45°. Utilizing Explore Mode in the simulation software with a fidelity/mesh size of 1.5 mm enables efficient analysis. Figure 7 illustrates the resulting geometry, showcasing a reduced mass of 1.74 kg compared to the original 2.9 kg. It's imperative to maintain vigilance throughout the optimization process to ensure that the safety factor remains above one, as a safety factor below this threshold could compromise the structural integrity of the design. For a more detailed exploration of the topology optimization process and how to interpret and validate the results, you can refer to the "Design for Metal Additive Manufacturing Part 2: Topology Optimization and Build Preparation" case study.

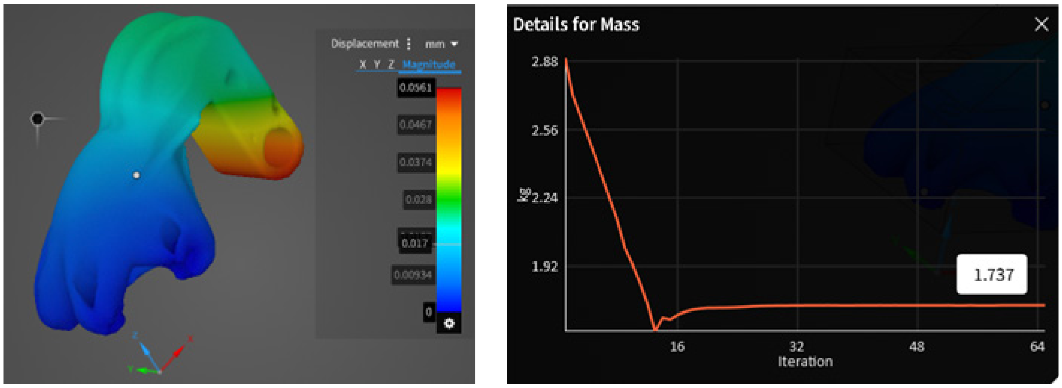
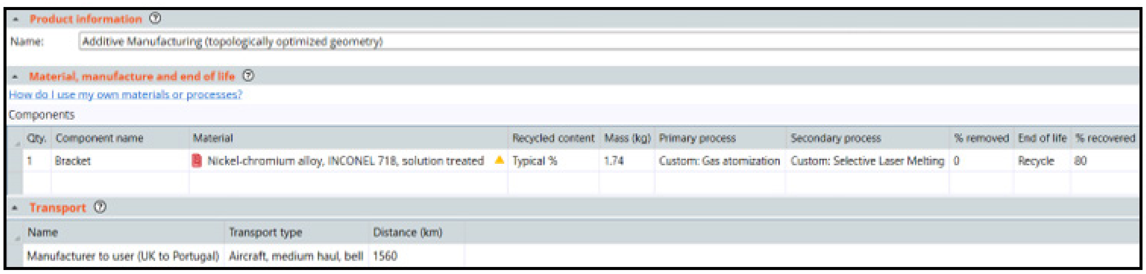


Figure 7 – (a) Topology optimized bracket with the color coding for the displacement. (b) Chart showing how the mass of the bracket changes from 2.9 kg, through the different iterations of the topology optimization process, before converging to 1.74 kg.

Having obtained the mass value of the topologically optimized bracket from Ansys Discovery, we can now delve into assessing the environmental implications of manufacturing this component using AM. To proceed, we'll utilize the Eco Audit tool in EduPack and initiate a new product comparison through the "Compare with…" functionality. Figure 8 illustrates the new bill of materials, where Inconel 718 undergoes gas atomization into powder before being additively manufactured into the optimized bracket geometry using the selective laser melting (SLM) process.



Product information

Name: Additive Manufacturing (topologically optimized geometry)

Material, manufacture and end of life

How do I use my own materials or processes?

Components

Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	Secondary process	% removed	End of life	% recovered
1	Bracket	Nickel-chromium alloy, INCONEL 718, solution treated	Typical %	1.74	Custom: Gas atomization	Custom: Selective Laser Melting	0	Recycle	80

Transport

Name	Transport type	Distance (km)
Manufacturer to user (UK to Portugal)	Aircraft, medium haul, bell	1560

Figure 8 - Bill of materials and transportation needs being considered in Eco Audit for the second scenario in which additive manufacturing is used to produce the topology optimized design of the bracket.

Both the primary and secondary processes employed are Custom processes, indicating that they are user-added. Environmental impact data from Table 1 has been incorporated for these processes. For further guidance on integrating your materials or processes data into Eco Audit, you can refer to the link provided beneath the "Materials, manufacture, and end of life" header in Eco Audit.

Table 1 - Environmental impact data used in the Eco Audit analysis in regard to gas atomization and SLM [5]

	Process energy (MJ/kg)	**Climate change (CO2-eq) (kg/kg)**
Gas atomization of Inconel 718	55	7
Selective laser melting of Inconel 718	427	52

The Eco Audit Summary Chart in Figure 9 offers a visual representation of the two scenarios under scrutiny. Although the SLM process exhibits a markedly higher environmental impact during the Manufacturing phase compared to machining, the crucial consideration arises from the topologically optimized geometry being 40% lighter than the original design. Consequently, this disparity in mass means that the Material phase eclipses the Manufacturing phase entirely. This shift is partly attributed to the substantial embodied energy of the Inconel 718 alloy, which heavily influences the material phase within this life cycle audit. It prompts us to question whether Inconel 718 is indeed the optimal material choice for this specific application. For further exploration of how we can select the optimal material for this bracket, refer to the "Design for Metal Additive Manufacturing Part 1: Materials Selection and Process Parameter Optimization" case study. In conclusion, the analysis suggests that manufacturing the topologically optimized bracket using SLM could yield a 36% reduction in energy consumption and a 25% decrease in Climate change (CO2-eq) compared to machining the original bracket geometry.

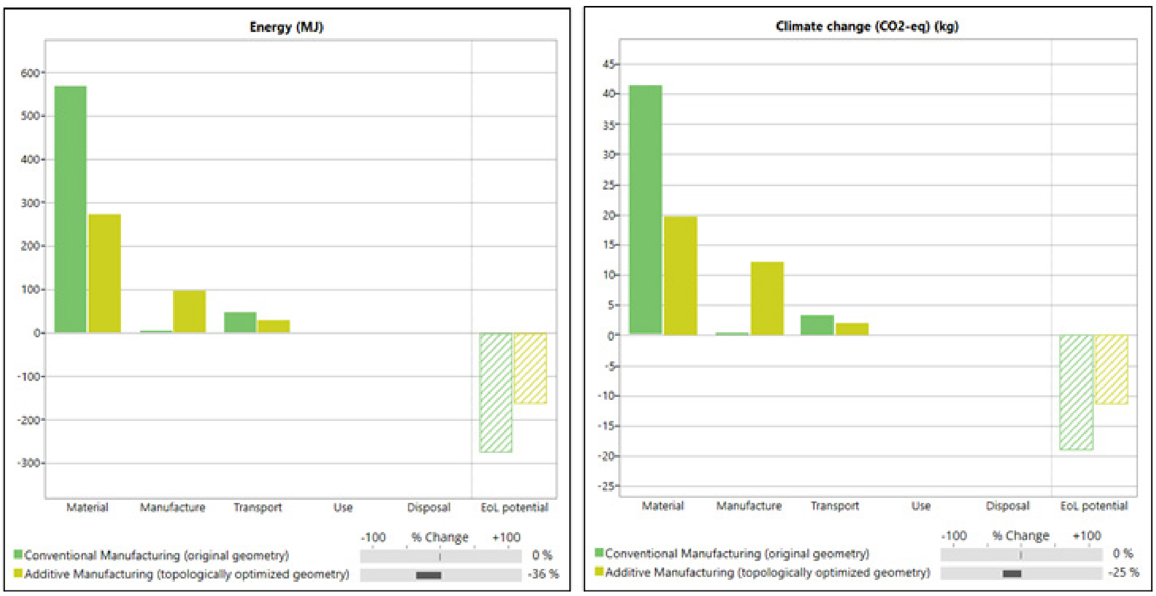


Figure 9 – Eco Audit summary charts displaying the Energy requirements and CO2 footprint of the two manufacturing scenarios, highlighting SLM's higher environmental impact during Manufacturing, while the lighter optimized design shifts focus to the Material phase.

Up until this point, we had only considered the Material, Manufacturing, Transport and End of Life phases of the life cycle, but of course for a full life cycle audit, we need to include the Use phase of the bracket as well. For this, we will assume that, in both scenarios, this bracket will be a part of a long-haul aircraft, being used for a year, traveling for 250 days per year and 15,000 kilometers per day (roughly equivalent to a return trip from Lisbon to Vancouver), as shown in Figure 10.

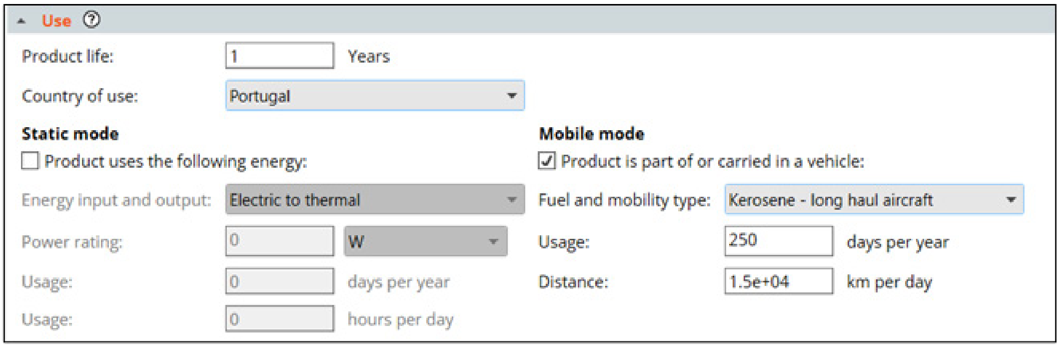


Figure 10 - Including the Use phase of the bracket in the Eco Audit analysis, assuming that it will be a part of a long haul aircraft, being used for a year, traveling for 250 days per year and 15,000 kilometers per day

Upon examining the Summary Charts in Figure 11, it becomes evident that the Use phase overwhelmingly dominates this bracket's life cycle in both manufacturing scenarios. Furthermore, transitioning to additive manufacturing for the topology-optimized bracket indicates a promising 40% reduction in both Energy requirements and Climate change (CO2-eq) compared to machining the original bracket geometry. This underscores the profound environmental impact of the aeronautical industry, particularly through its fuel consumption.

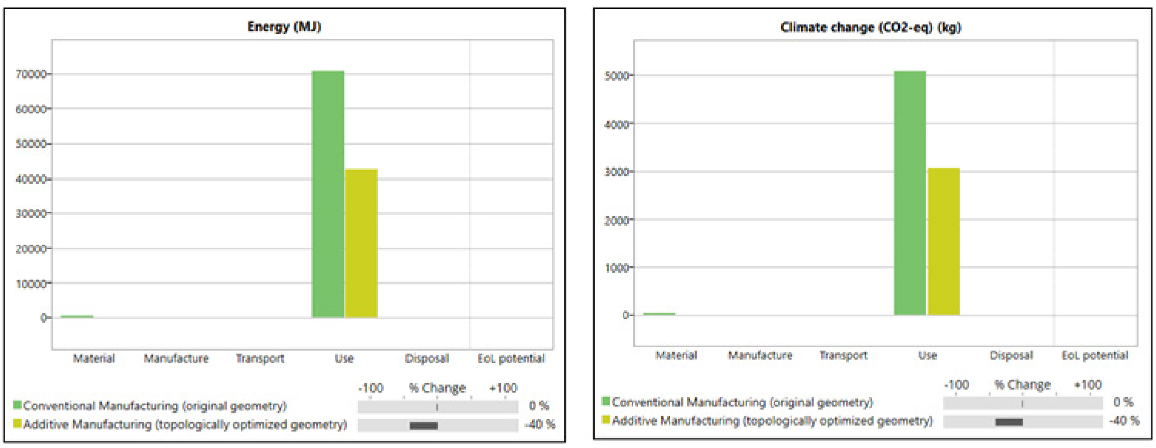


Figure 11 - Eco Audit summary charts after including the Use phase, highlighting that the Use phase dominates this bracket's life cycle in both manufacturing scenarios and that using AM can reduce the environmental impact by 40%.

3. Conclusions

The eco-impact of manufacturing an aeronautical bracket is explored through conventional machining and Additive Manufacturing (AM) processes. In the conventional manufacturing scenario, the bracket's original design facilitates machining with Inconel 718 material, resulting in a substantial environmental impact primarily driven by the material phase due to machining waste and the component's large mass. Conversely, AM offers the potential for lightweighting through topology optimization, significantly reducing the bracket's mass and potentially mitigating environmental impacts. Despite AM's higher environmental impact compared to machining, the lightweighted design overshadows this disadvantage, demonstrating potential energy savings and reduced CO2 emissions. Overall, transitioning to AM for the topologically optimized bracket could yield a 36% reduction in energy consumption and a 25% decrease in Climate change (CO2-eq) compared to conventional machining methods.

4. Reality check

Keeping the three capitals of sustainability in mind, the economic and environmental implications of AM are multifaceted, encompassing both advantages and drawbacks. Despite its potential to reduce environmental impacts and production costs, AM can inadvertently exacerbate them. One significant environmental disadvantage of AM lies in its material feedstock, particularly metal and polymer powders, which demand energy-intensive production processes. Additionally, the slow production rate of AM machines contributes to increased energy consumption during prolonged operation. Moreover, post-processing operations, essential for refining surface finishes and removing support structures, incur additional environmental costs. From an economic standpoint, the production costs associated with AM can be considerably higher than traditional manufacturing methods, primarily due to expensive feed material and support structures, along with extensive post-processing requirements. However, the benefits and challenges of AM extend beyond environmental and economic considerations alone. From a social perspective, AM's widespread adoption has the potential to reshape traditional manufacturing paradigms, offering decentralized production capabilities and fostering local manufacturing ecosystems. By enabling customized, on-demand production, AM promotes resource efficiency and reduces waste, aligning with broader sustainability goals. Furthermore, the democratization of manufacturing facilitated by AM empowers small-scale entrepreneurs and communities, driving innovation and economic growth. Yet, challenges remain, including accessibility barriers, workforce retraining needs, and equitable distribution of technological benefits. Thus, while AM holds promise as a transformative technology for sustainability, its social impacts warrant careful consideration to ensure inclusive and equitable outcomes for all stakeholders.

5. References

[1] World Commission on Environment and Development, "Our Common future," 1987.

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[5] S. Torres-Carrillo, . H. R. Siller, . C. Vila, C. López and C. A. Rodríguez, "Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades," Journal of Cleaner Production, vol. 246, 2020.

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