ORIGINAL RESEARCH COMMISSIONED BY

AMGTA ADDITIVE MANUFACTURER GREEN TRADE ASSOCIATION

ADDITIVE SUSTAINABILITY

March 28, 2023

Life Cycle Assessment (LCA) Report

Comparison of a Low-Pressure Turbine (LPT) Bracket by Two Manufacturing Methods

Prepared by

RIT | Golisano Institute for Sustainability

Rochester Institute of Technology

INTRODUCTION

The Additive Manufacturer Green Trade Association (AMGTA) is the only global organization bringing together companies throughout the manufacturing ecosystem to promote and elevate the conversation around additive practices as an environmentally beneficial strategy for addressing lead-times, supply chains, waste-streams, energy consumption, technological advancements, and overall environmental and societal impacts. This informed and ongoing collaboration between AM technology developers and practitioners is enabling the AM industry to address the need and demand for more sustainable manufacturing and more resilient and flexible supply chains in a strategically, financially, and environmentally beneficial way. Fundamentally, the AMGTA brings together the manufacturing and sustainability communities to better understand the leverage-potential of additive manufacturing.

AMGTA members represent the entirety of the manufacturing ecosystem—from design and source materials to end products and users. These members demonstrate their industry leadership by working together to address the compelling issues around rapidly evolving manufacturing demands, stakeholder expectations, geo-political events, climate impacts and a changing ecology. Through member forums, rigorous research, and business use-case analysis the AMGTA works to better understand and communicate the direct impacts and potential of additive manufacturing and the marketplace demand for more sustainable manufacturing to increase acceptance and adoption of additive practices.

The AMGTA works with member organizations to raise the profile of their sustainability efforts and the potential for more sustainable manufacturing through their products, services, and systems. The AMGTA represents its members at additive manufacturing industry forums and conferences to promote the environmental benefits of additive practices. The AMGTA also represents its members within the sustainability community to promote the power and potential of additive power and potential of additive practices to deliver on bold environmental goals. We engage member organizations in ground-breaking research projects and business case studies to better understand the potential of AM, inform ongoing industry development, and increase acceptance and adoption of more sustainable manufacturing practices.

The AMGTA is engaging AM technology leaders, the broader manufacturing industry, and the overall sustainability community in an independent and comprehensive way in which no one company, regardless of size or position in the market, can do on its own.

Message from the Executive Director

The release of this peer-reviewed LCA—the first of its kind—represents a milestone for the AMGTA. For the first time, we are able to publish tangible results demonstrating the importance of design in AM manufacturing when compared to traditional methods. This study demonstrates the very real impact that AM can have in aircraft and engine design of the future and bodes well for using similar strategies in other industries and programs.

The two phases of this study—production and use—have implications well beyond this specific bracket, aircraft, or even manufacturing sector. The negligible difference in environmental impacts during production combined with the benefits of on-demand production—when you want it, where you want it, how you want it—to deliver more resilient, efficient, and sustainable supply chains, have significant implications for the manufacturing ecosystem to deliver more sustainable solutions.

While this study has immediate implications for aircraft engine and air-frame manufacture, the findings in the use phase extend to any part of an airplane that could potentially be lightweighted—mechanical systems, seats, service carts, gallies—and well beyond aircraft to any equipment moved by an engine or motor—vehicles, ships, trains, robots—although the energy demands for aerospace make it the biggest, most obvious and most immediate beneficiary.

Sherri Monroe
Executive Director, AMGTA
March 2023

Message from the AMGTA Board Chairman

This study underscores the importance of using AM to develop optimized parts and components that have been lightweighted via AM technology. No other currently viable commercial technology offers such an immediate impact to carbon emissions as lightweighting aircraft parts via AM does, and we now have independently verified, peer-reviewed data proving so. We look forward to working with all of the industry's OEMs as the look to unleash the sustainable potential of AM across existing and future platforms.

Brian Neff
Board Chair, AMGTA
Founder & CEO, Sintavia, LLC
March 2023

Comparative LCA of a Low-Pressure Turbine (LPT) Bracket by Two Manufacturing Methods

This life cycle assessment, commissioned by the AMGTA and authored by the Rochester Institute of Technology's Golisano Institute of Sustainability, analyzed a commercial aerospace low-pressure turbine bracket via a life cycle assessment ("LCA"), evaluating both (i) the comparative manufacturing impact of laser powder bed fusion ("LPBF") additive manufacturing ("AM") vs. traditional manufacturing of the bracket and (ii) the impact of a greater than 50% weight reduction of the bracket over the life of the aircraft. While the comparative end-result was inconclusive with regard to which manufacturing method used more energy, the results confirmed the dramatic impact that lightweighting commercial aircraft engines, airframes, and other parts have on carbon emissions.

Key takeaways from the LCA included the following points.

- **Outsized Impact on Lightweighting Aircraft.** The study very clearly showed that lightweighting aircraft components via AM design resulted in a dramatic reduction in carbon emissions over the life of an aircraft, with a reduction of 13,376 kg for every 1 kg of weight reduction.
- **Importance of Energy Mix.** The study found that by far the biggest factor in determining sustainability of production was a manufacturing facility's energy mix at the location of generation, and whether that energy grid was produced using sustainable means.
- **Inconclusive on Manufacturing Method.** Using three separate methodologies, the LCA was inconclusive as to which manufacturing method (traditional or additive) used more energy. On balance, this neutral finding represented an improvement over previous studies showing higher energy used in LPBF manufacturing compared to traditional methods.
- **Overall, AM Produced a More Sustainable Part.** The impact of lightweighting by far was the most important factor in determining that AM-produced components are more sustainable than a traditionally designed and manufactured part.

The two-year study analyzed the two brackets using three LCA methodologies, including the ReCiPe 2016 version 1.1 midpoint method, the Cumulative Energy Demand v1.11, and the Intergovernmental Panel on Climate Change's IPCC 2021 GWP100 methods. Two of the three methods indicated that, strictly from a manufacturing standpoint, the traditional bracket required less energy to produce, while one method indicated that the AM version produced less carbon dioxide. In all cases, however, the results indicated that the energy mix of the underlying electrical grid had an outsized effect on the sustainability of the manufacturing process. The LCA was performed in accordance with ISO 14040:2006(E) and was peer-reviewed by EarthShift Global.

continued

Comparative LCA cont'd.

The underlying bracket, which is one of 12 on each of the two GE Aviation CF6-80C2B6F turbine engines powering a Boeing 767 aircraft, secures a fuel manifold to the external case of the engine's low pressure turbine module. It was selected by the AMGTA because it was a relatively simple part that is easy to access and locate. The additive design and manufacturing of the bracket was performed by Sintavia, LLC in Hollywood, Florida, and printed on an EOS GmbH M290 printer using Höganäs AB Inconel 718 powder. The traditional part was manufactured by a Tennessee-based machine shop using a CNC process. The optimized AM bracket was over 50%, or 0.063 kg, lighter than the original version. According to Sintavia, the optimized bracket outperformed the traditional bracket in terms of mechanical properties, with an increased fatigue life in spite of its reduced weight.

A comparison of the AM-designed bracket (left) and the traditional version (right).

While the choice of the LPT bracket offered a simple demonstration of how lightweighting could work on an aircraft engine, the AMGTA believes that the lessons embodied in the current LCA could be much more widely adopted by airframers and engine manufacturers across multiple mechanical systems. Moreover, lightweighting methods of transportation using additive design technology is not only limited to LPBF AM, as other additive technologies (including binder jetting, directed energy deposition, and polymer printing) can similarly remove excess weight across vehicles, aircraft, and vessels.

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RIT | Golisano Institute for Sustainability

Life Cycle Assessment (LCA) Report:

Comparative LCA of a Low-Pressure Turbine (LPT) Bracket by Two Manufacturing Methods

FINAL REPORT

Date Prepared:
March 28, 2023

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Prepared for:
AMGTA

Acknowledgements and Disclaimers

This Life Cycle Assessment (LCA) report is prepared consistent with the terms and purposes of the Research Agreement between Additive Manufacturing Green Technology Association (AMGTA) and Rochester Institute of Technology (RIT) on behalf of the Golisano Institute for Sustainability (GIS) that was effective August 12, 2021. All conclusions herein are subject to the research warranty and liability limitations, and other provisions, described in the Research Agreement executed by RIT and AMGTA.

RIT and GIS cannot endorse any particular product or service. This report is the result of the tests and/or studies conducted and described; it is not to be interpreted as any type of specific endorsement of any product or service.

AMGTA may use this report externally if used in its entirety. Any other use of less than a complete version of this report is allowed only if AMGTA first obtains the written permission of RIT.

This LCA was performed in accordance with ISO 14040:2006(E) *Environmental management—LCA—Principles and framework*. In accordance with ISO 14044:2006 section 7 Critical Review, this report was reviewed by a critical review panel to assure that the LCA has met the requirements for methodology, data, interpretation and reporting, and verify that it is consistent with the standard principles.

Executive Summary

The following report presents the results of a life cycle assessment (LCA) completed by the Golisano Institute for Sustainability (GIS) at Rochester Institute of Technology (RIT) on behalf of the Additive Manufacturer Green Trade Association (AMGTA).

The goal in conducting this LCA was to provide AMGTA, and more broadly the additive manufacturing (AM) industry, with a better understanding of the potential impacts of an additive-manufactured low-pressure turbine (LPT) bracket as part of a lighter weight, less fuel-intensive aircraft design. Using the LPT bracket in a GE CF6-80C2 jet engine as the focus of this study, GIS compared the environmental impacts of a set of examples produced through AM to a baseline set that were traditionally machined. Results of this study are intended to be disclosed to the public.

The type of LCA was a comparative-assertion study and was ISO 14040-compliant. This report was peer-reviewed to ensure methodology, data, assumptions, results, and conclusions are accurate. The peer review was conducted by a panel of three LCA experts in accordance with ISO requirements.

Overview

A fundamental question that AMGTA aimed to answer through this LCA was whether an AM-made LPT bracket would contribute to significant fuel savings over the lifetime of an aircraft. This inquiry follows from AM's widely recognized value to a materially efficient design approach: Whereas traditional machining "subtracts" from a solid stock of metal alloy to make components like the LPT bracket, AM "adds" only what is minimally needed. A growing body of research suggests that building up material is an advantage for lightweighting plane components that, writ large, can lead to a lighter aircraft that, in turn, uses less fuel.

The LCA illuminated the phase in the two upstream supply chains (cradle-to-gate phases) the most impact originates. In both cases, this was the manufacturing phase. All other phases were almost identical in regards to energy use and emissions. It was also observed that differences in the size and shape of raw materials used during traditional manufacturing significantly affected sustainability measures.

It was discovered that a manufacturing facility's local energy mix—regardless of whether it uses AM or traditional processes—can override other factors when it comes to impacts. The energy source (e.g., fossil fuels, nuclear, or renewables) powering a grid has a significant impact on a manufacturer's electricity use and emissions.

Ultimately, the above variables made it difficult to generalize the findings of the case studies into broader conclusions about AM's merits as an enabler of greener aviation.

With this in mind, a different research pathway was pursued: A model was designed that simulates a long-haul, transatlantic flight between London and Boston. It drew on the data results from the LCA and publicly available data to estimate how an AM-made, lightweighted LPT bracket might lower a plane's overall mass and, consequently, reduce how much fuel it uses over its lifetime. This phase of the research indicated strongly that lighter parts can reduce fuel use over the course of an aircraft's life.

This study assumed that the AM-designed bracket achieved the same performance and function as the actual machined component, and that it met all industry requirements and specifications; we did not validate this assumption as part of this project.

AMGTA was also interested in better understanding the impacts related to AM of this bracket.

Methodology

The LCA documented in this report models life cycle impacts in 18 categories as represented in the ReCiPe 2016 version 1.1 midpoint method (hereafter referred to as "the ReCiPe method"). The life cycle impacts were also modeled using the cumulative energy demand v1.11 ("CED") methodology, and Intergovernmental Panel on Climate Change's IPCC 2021 GWP100 ("GWP100"), which is a measure of a gas's potency as a contributor to global warming over one hundred years. Data from both the traditional and AM processes were modeled using all three of the aforementioned methodologies.

This study measured the cradle-to-gate impacts of the two differently made LPT brackets. The models developed for this analysis relied on data collected from the following sources:

- Case studies: Two manufacturers produced test LPT brackets for the study, one used AM and the other used conventional machining. The companies were located in the U.S. states of Florida and South Carolina, respectively.
- LCA database: Ecoinvent 3.8, a database that is compiled from peer-reviewed LCAs and datasets that cover over 10,000 processes.
- Scientific literature review: GIS conducted a thorough review of existing literature comparing the life cycle impacts and material performance of components similar to LPT brackets.

For the flight fuel-use and emissions model created, the analysis relied on fuel economy data for a Boeing 767 as reported using the 2019 EMEP/EEA Air Pollutant Emissions Calculator. Fuel-consumption models are based on actual flight data collected through aviation operations in Europe.

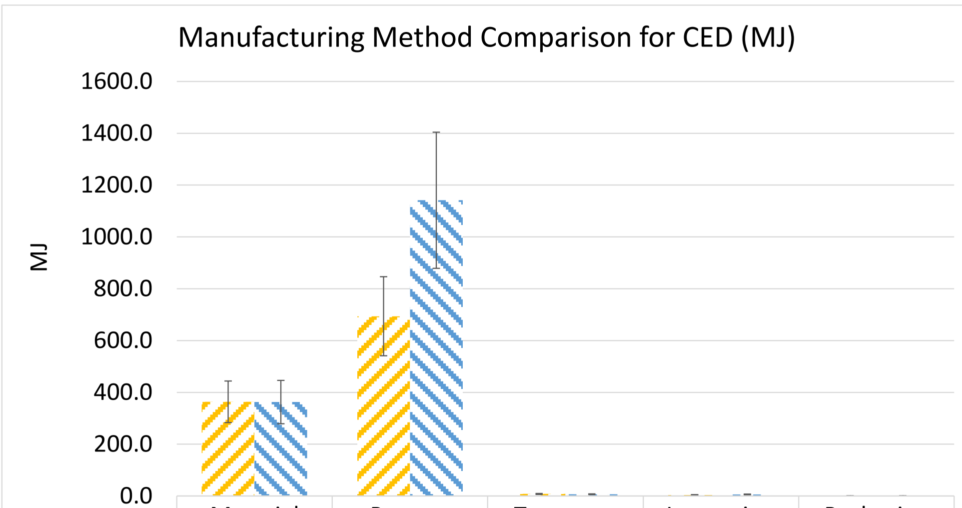
All results in this summary are stated as analysis averages. Data-quality analyses are included in the corresponding report sections.

Key Findings

Phase 1: Case study analysis

Impact of manufacturing process

A breakdown of the life cycle categories for each method shown in Figure 1 (CED analysis) and Figure 2 (GWP100 analysis) both indicate that the process stage of the cradle to gate manufacturing phase, is the most impactful phase in both instances. Otherwise, the remaining categories are nearly equivalent between the two.



	Material	Process	Transport	Inspection	Packaging
Additive	363.7	693.8	8.1	4.17	0.62
Traditional	362.7	1141.6	6.6	6.51	0.62

Figure 1: Comparison of cradle-to-gate life cycle categories for CED

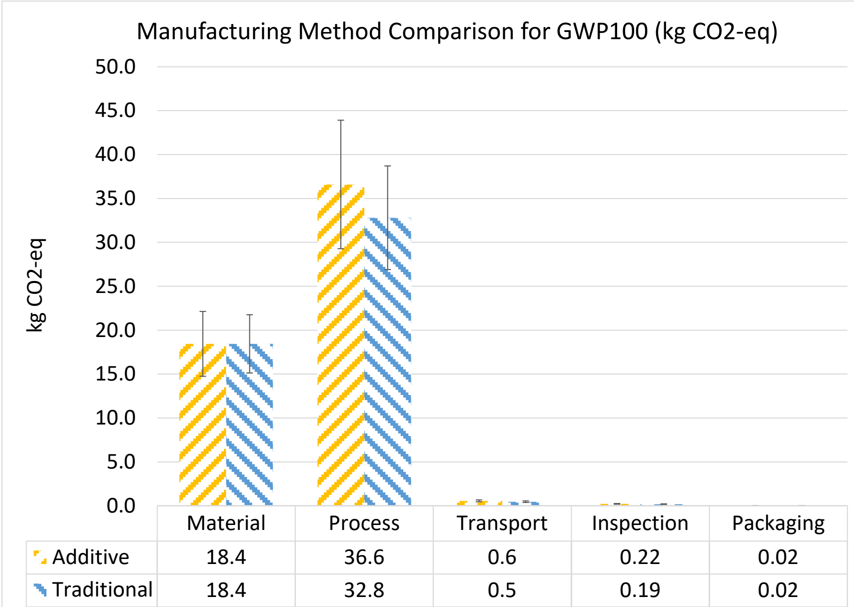


Figure 2: Comparison of life cycle categories cradle-to-gate for GWP100

Out-sized influence of local energy mix

Figures 3 and 4 illustrate the difference in energy use and carbon emissions respective to AM and traditional manufacturing according to different energy-mix models. “Specific mix” refers to the electricity used by the actual manufacturing locations in this study. Because of the variability of energy service from one locale to another, we could not clearly determine whether either of the case studies was, in all aspects, more sustainable than the other. The error bars displayed in the charts show the standard error between the different energy mixes for each manufacturing method.

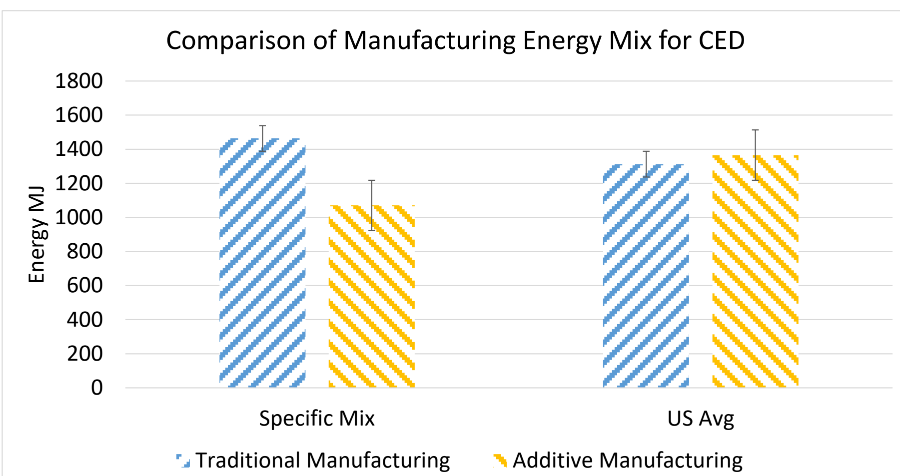


Figure 3: Energy-mix impacts on manufacturing for CED

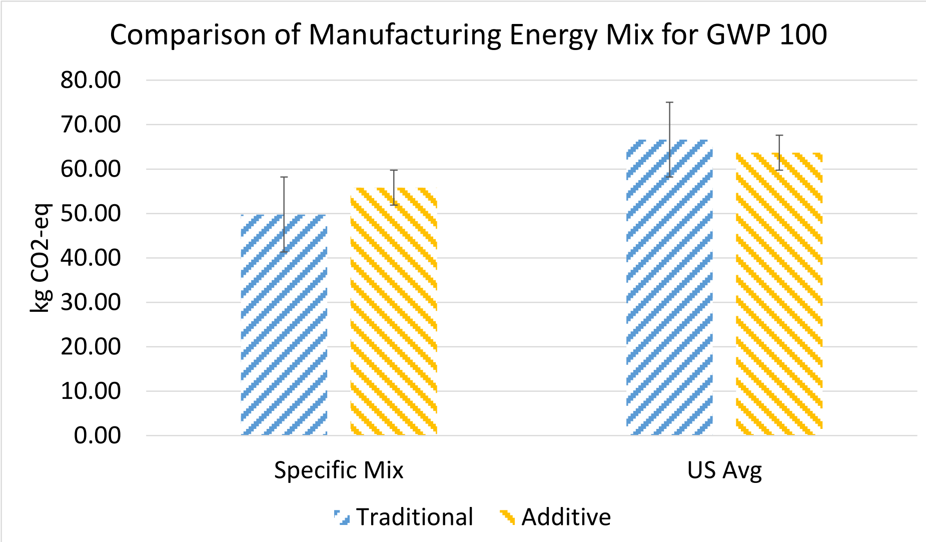


Figure 4: Energy-mix impacts on manufacturing for GWP 100

Material stock size as important factor

Oversized material stock will have a greater impact during the material production phase through to the manufacturing phase, when additional material is removed during machining, as shown in Figures 5 and 6. The round bar stock used in this study would not be feasible in a production setting. The square bar or plate can be sized more closely to the required part dimensions to reduce required material input and resulting waste from the manufacturing process.

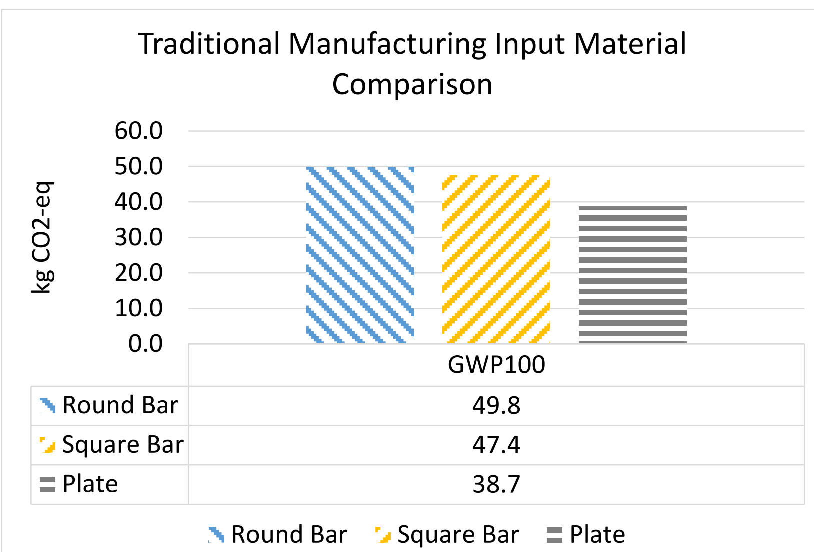


Figure 5: GWP 100 impacts of traditional manufacturing input-material size

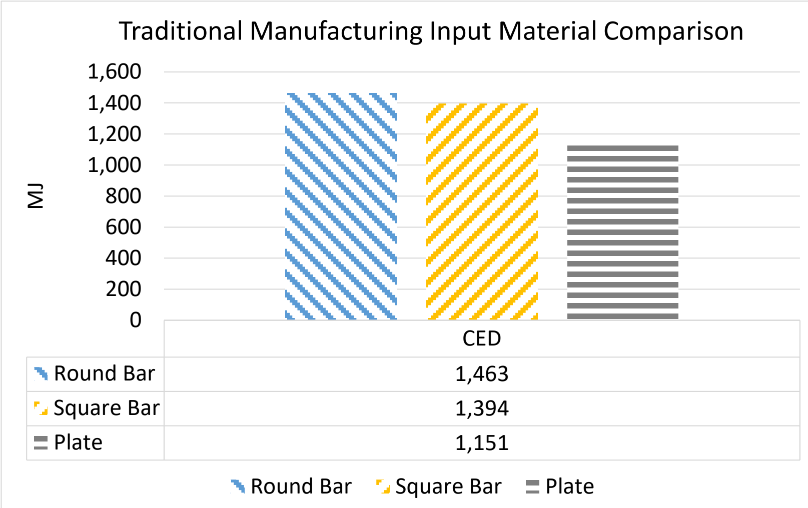


Figure 6: CED Impacts of traditional manufacturing input-material size

Limitation of conclusions from LCA data

Figure 7 shows how each of the three analysis methods employed to compare the two manufacturing technologies leads to a different perspective. The left chart for CED suggests that AM requires less energy than traditional manufacturing in the regions covered by this study when the CED methodology is used, which focuses on energy mix. However, the right-hand chart presents a different conclusion, where traditional manufacturing seems to perform better than AM under a GWP100 analysis. Uncertainty analysis will show that these results are inconclusive for the manufacturing cradle to gate phase of the life cycle.

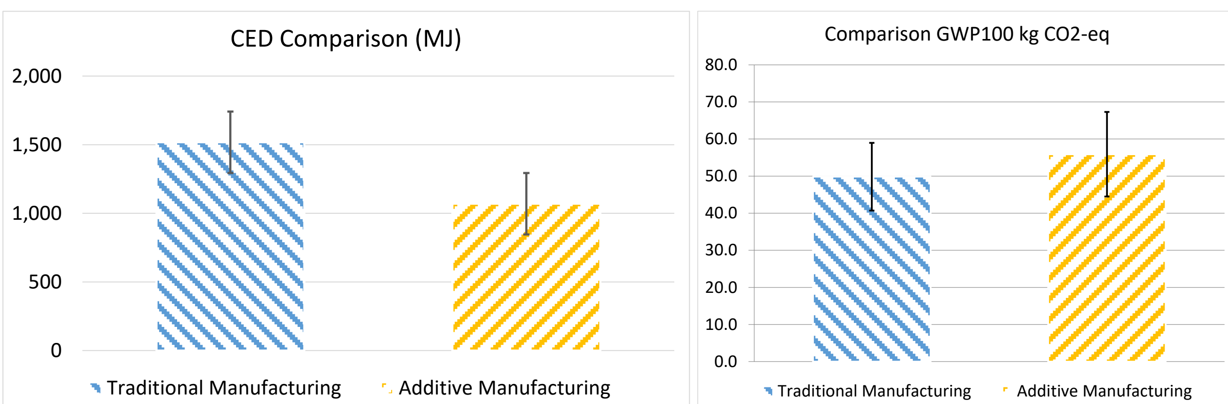


Figure 7: Comparison Cradle-to-gate of CED (left) and GWP100 (right) impacts

Likewise, Figure 8 compares the two manufacturing methods according to the ReCiPe method. The results of this analysis illustrate the relationship between traditional manufacturing and AM for one specific scenario modeled. As previously mentioned, the uncertainty analysis determined results are inconclusive for the cradle to gate lifecycle phase.

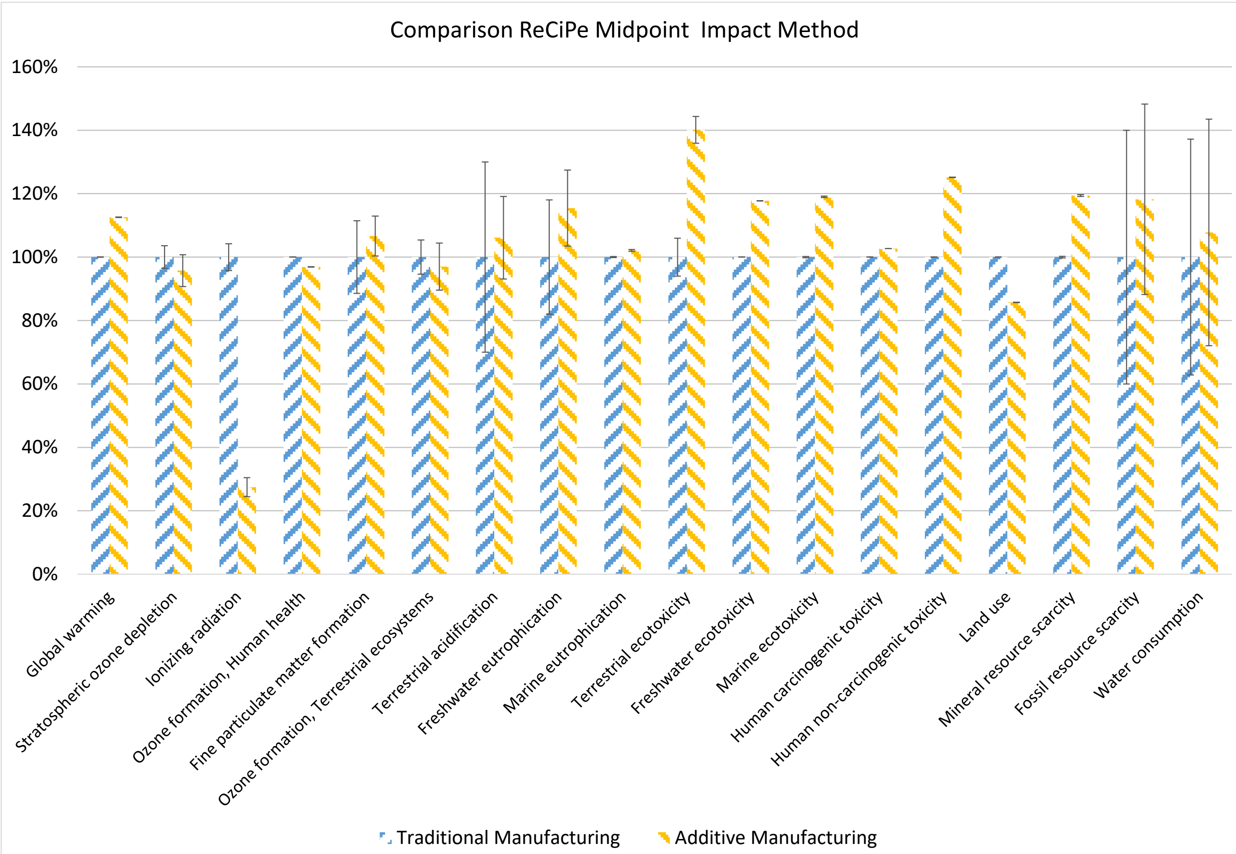


Figure 8: Comparison of manufacturing methods according to the ReCiPe method

Phase 2: Flight fuel-consumption model

Lightweighting parts to cut aviation emissions

The results of the study's second phase—the long-haul flight model of a Boeing 767 flying from London to Boston—indicate that lowering the weight of components used in a commercial aircraft can effectively reduce its carbon footprint. In fact, GIS concluded that lightweighting of components alone is enough to counterbalance the total impacts of the aircraft's cradle-to-gate life cycle phase.

Table 1: Total GWP100 Comparison

GWP100	Total 1 Bracket[a]	Total 24 Brackets	Units
Additive	55.83	1,340	kg CO2-eq
Traditional	49.77	1,195	kg CO2-eq

Note. [a]Low-pressure turbine (LPT) brackets as used in a GE CF6-80C2 jet-engine assembly.

Flight-related impacts for the use-phase of the 24 installed brackets were modeled separately to show the potential savings through the use of lightweight materials. These savings include emissions from both fuel production and aircraft operation. The data shown in Figure 9 (a GWP100 analysis) indicate a lifetime savings of 21,565 kg CO2-eq for 125,000 flight hr.

The total GWP for the AM process is 1,340 kg CO2-eq (Table 1). Based on the lifetime savings of 21,565 kg CO2-eq, the net savings would be approximately 20,225 kg CO2-eq for the LPT brackets made using AM.

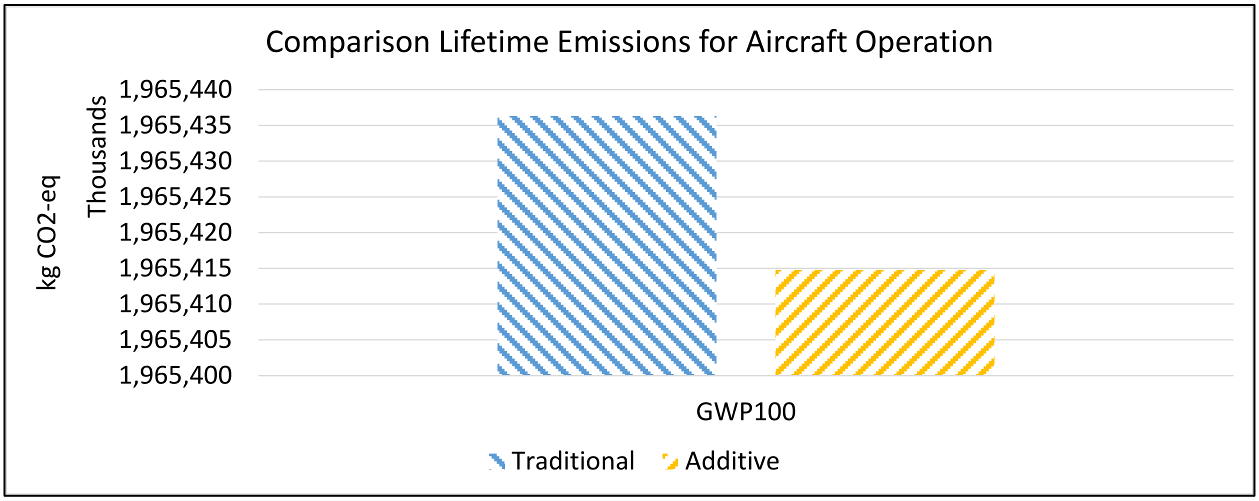
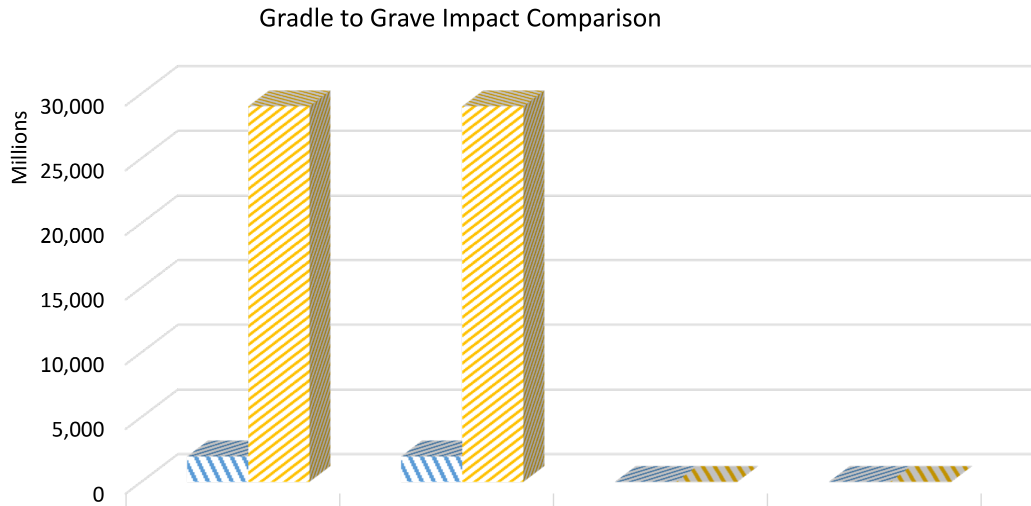


Figure 9: Comparison of lifetime operation emissions between aircraft with traditionally manufactured LPT bracket and one with AM-produced LPT bracket

A comparison of the cradle-to-gate manufacturing phase to the use phase is illustrated in Figure 10, which shows that the use phase impacts significantly outweigh manufacturing impacts for 24 brackets.



	Traditional Flight	Additive Flight	Traditional Manufacture	Additive Manufacture
GWP100 (kg CO2-eq)	1,965,436,262	1,965,414,697	1,195	1,340
CED (MJ)	29,022,873,194	29,022,554,757	1,463	1,070

Figure 10: Comparison of Cradle-to-grave Impacts for CED and GWP100

This study looked at an isolated scenario of changing mass between two identical planes and potential fuel savings over the expected useful life of the planes. It is understood that other variations within the aircraft might outweigh the potential savings from a very small part.

Next Steps

Further investigation is needed into the impacts associated with the production of the powder used to additively manufacture the brackets in this study, Inconel 718 powder. There is limited data that is currently publicly available on this subject.

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Abbreviations and Glossary

Abbreviations

ACLCA	American Center for Life Cycle Assessment
AMGTA	Additive Manufacturing Green Trade Association
AM	additive manufacturing
APOS	Allocation at the point of substitution
ASTM	ASTM International
CCD	climb, cruise, and descent
CED	cumulative energy demand
CFC-11	trichlorofluoromethane
CMM	coordinate-measuring machine
CNC	computer numerical control
CO2-eq	carbon dioxide (CO_2) equivalent
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EOL	end-of-life
eq	equivalent
FEA	finite element analysis
GIS	Golisano Institute for Sustainability
GLO	Ecoinvent geographic location for data: GLO = Global
GWP	global warming potential
GWP100	global warming potential over 100 year time interval
HP	horsepower
hr	hour
ICAO	International Civil Aviation Organization
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
Kg	kilogram
Km	kilometer
kW	kilowatt
lb	pound
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment

LTO	landing and take-off
m	meter
MJ	megajoule
N	nitrogen
nmi	nautical mile
O3 (O_3)	ozone
RER	Ecoinvent geographic location for data: RER = European
RIT	Rochester Institute of Technology
SO2 (SO_2)	sulfur dioxide
U.S.EPA	U.S. Environmental Protection Agency
U.S.LCI	U.S. life cycle inventory database

Glossary

Ecoinvent	Ecoinvent is a commercially available database which is compiled from peer-reviewed LCAs and data sets and covers over 10,000 processes.
Functional Unit*	A unit of production or output against which category indicator results are normalized.
Impact*	A negative effect to human health or the environment, the depletion of resources or disturbance of natural ecological biomes.
Impact Category*	An environmental or human-health impact that can be measured or observed.
Input*	Product, material or energy flow that enters a unit process.
Life Cycle*	Consecutive and interlinked stages of a product, service, or system, from raw-material acquisition or generation from natural resources to final disposal.
Life Cycle Assessment (LCA)*	Compilation and evaluation of the inputs, outputs, and environmental and human-health impacts of a product, service, or system throughout its life cycle.
Life Cycle Impact Assessment (LCIA)*	The LCA phase in which the magnitude and significance of the environmental and human-health impacts of a product or system are evaluated throughout the life cycle, considering each node along the stressor-effects network.
Life Cycle Inventory (LCI)*	The LCA phase involving the identification, compilation, and quantification of inputs and outputs that are associated with a given product or system throughout its life cycle.
Output*	A product, material, or energy flow that leaves a unit process.
SimaPro	SimaPro is a commercially available LCA software tool with integrated databases and impact assessment methods that enable modeling of the environmental impacts of products, processes, or systems.

1 Introduction

Weight has a direct effect on how much fuel an airplane uses, making it a key design consideration when it comes to reducing greenhouse gas (GHG) emissions and environmental impact within the aviation industry. As such, additive manufacturing (AM) is receiving increasing attention from the industry as a tactic for lightweighting aircraft. Many airplane part designs are constrained by traditional machining processes. However, as new processes like AM are developed, tested, and validated, designers have more freedom to create less heavy designs that provide the same functionality.

A traditional bracket is made from Inconel 718 alloy. Today, all brackets are manufactured using conventional machining to meet specific quality and performance standards.

AM has a greater potential for improving efficiency of material use and part-design functionality compared to traditional manufacturing methods. Aerospace component manufacturers are adopting components designed for and manufactured by additive processes due to their lightweight and cost-effective designs.[1] AM can reduce the cradle-to-gate environmental impacts through avoidance of the materials, processes, and scrap associated with traditional manufacturing. Additionally, the potential to reduce fuel use and associated emissions during the use phase of a commercial aircraft due to reduced material weight is of interest: An AM-produced bracket is made from Inconel 718 powder.[2]

1.1 Life Cycle Assessment

For this project, the Golisano Institute for Sustainability (GIS) team at Rochester Institute of Technology (RIT) investigated the environmental impacts of low-pressure turbine (LPT) brackets (one made using AM, the other traditionally made) using established life cycle assessment (LCA) methodology. LCA is a tool used to quantify the environmental impacts associated with all phases of a product or process life from cradle-to-grave; from material extraction to manufacturing, transportation, use, and, ultimately, through end-of-life management. LCA helps identify environmental impacts by compiling an inventory of energy and material inputs and environmental releases, evaluating the potential impacts associated with those inputs and releases, and then interpreting the results to help stakeholders make more informed decisions (reference ISO 14040:2006).

LCA results are useful for communicating the environmental impact of a product both internally and externally. Internally, LCA results enable identification of operations or materials that contribute significant environmental impacts, allowing opportunities for improvement to be targeted. Externally, LCA results can be used to validate marketing claims or compare the environmental impact of products between multiple manufacturers.

A LCA is executed in four distinct phases: (ISO 14040, 14044)

Step 1: Definition of goal and scope—identify the LCA's purpose, the products of study, and determine the system boundaries (i.e. what is and is not included in the study). (See Chapter 3, "Goal and Scope.")

Step 2: Life-cycle inventory (LCI)—Quantify the energy and raw material inputs and environmental releases associated with each life cycle phase. (See Chapter 4, "Life Cycle Inventory.")

Step 3: Life cycle impact assessment (LCIA)—Assess impacts on human health and the environment. (See Chapter 5, "Life Cycle Impact Assessment (LCIA).")

Step 4: Result interpretation—Evaluate opportunities to reduce energy, material inputs, or environmental impacts at each stage of the product life-cycle. (See Chapter 6, "Results.")

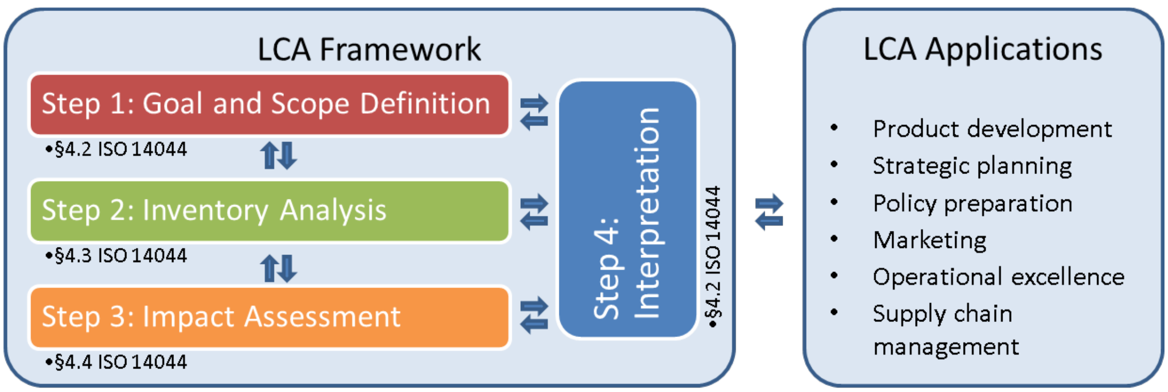


Figure 11: LCA framework

1.2 Involved Parties

Execution of this project involved technical staff from GIS and staff at AMGTA and Sintavia LLC (Sintavia), an AM company, to collect data and build representative models of the AM process using SimaPro 9.2 LCA software. Sintavia designs and manufactures advanced propulsion and thermodynamic systems for the next generation of aerospace manufacturers.[3] Sintavia technical staff was responsible for all AM process data collection with guidance from GIS staff. These SimaPro models were used to perform comparative analyses between the traditional and AM methods.

The machined-bracket model was built utilizing the relevant material, energy, and production data provided by Innovative Manufacturing & Design (Innovative), a traditional precision-parts manufacturer contracted through AMGTA to manufacture a part by traditional methods for the purpose of data collection. Process, energy and material data was collected and reported by Innovative. All other process and material data for both processes were derived from the Ecoinvent 3 materials and process database along with other published references.

The goal in conducting this LCA was to provide AMGTA, and more broadly the AM industry, with a better understanding of the potential impacts of an additive-manufactured LPT bracket as part of a lighter weight, less fuel-intensive aircraft design.

1.3 LCA practitioner

This project was completed by Allen Luccitti, an LCA specialist at GIS who assists with ISO 14040-compliant LCAs. He is a key resource for New York State Pollution Prevention Institute's (NYSP2I) Green Technology Acceleration Center and Sustainable Supply Chain and Technology programs. Mr. Luccitti holds a bachelor's degree of science and master's degree in mechanical engineering from RIT.

Technical staff and faculty within GIS include certified LCA professionals from the American Center for Life Cycle Assessment (ACLCA) who provide expertise and industry application of LCA methodologies. GIS conducts LCAs in accordance with ISO 14000 series standards for a broad range of industries, from the transportation sector to medical device manufacturers to office products. GIS may also function as an independent, third-party critical reviewer, providing a non-biased, independent evaluation of the methodology and interpretation of others' LCA results. These LCA results are used by clients to make informed decisions for strategic planning, priority identification, and product or process design or redesign. In addition, the LCA process enables companies to identify opportunities to improve environmental performance, and thereby supports competitiveness in the green marketplace.

1.4 Critical Review

This LCA was performed in accordance with ISO 14040:2006(E) *Environmental management—LCA—Principles and framework*. This report was peer-reviewed to ensure methodology, data, assumptions, results, and conclusions are accurate. The peer review was conducted by a panel of three LCA experts in accordance with ISO requirements.

2 Goal and Scope

LCA is used to identify or compare a product's full range of environmental impacts by quantifying all inputs and outputs of material flows and assessing how these material flows affect the environment. As is common with all LCAs, however, completing a comprehensive assessment for all potential effects requires an excessive amount of time, data, knowledge, and resources. It therefore follows that there are limits to the comprehensiveness and data quality of any analysis. The LCA goal and scope help outline how the study boundaries are drawn, where the analysis of the specific life cycle begins and where it ends, and identifies the processes included within the technical system. This section defines the boundaries of the study for each bracket and how the bracket weight can impact the fuel use of an airplane in flight.

2.1 Goal

The goal of this study was to compare the life cycle environmental impacts of an AM-produced engine-mounting bracket to those of a bracket that has been manufactured through traditional machining methods. AM enables the bracket to be designed with less material while still providing the same functional performance. This comparative study aimed to compare a light weight, AM-produced bracket to a traditionally manufactured part at the current specified weight.

Additionally, weight is known to have a significant impact on airplane fuel use. This study therefore, also looked at the difference that part weight has on fuel use, and compared the environmental impacts of fuel use from aircraft operation to the life cycle impacts of manufacturing the brackets.

This LCA was performed in accordance with ISO standards 14040:2006(E) ("Environmental Management—LCA—Principles and framework") and 14044:2006(E) ("Environmental Management—LCA—Requirements and guidelines").

2.2 Scope

This section defines the system products included in the study, the system boundaries, functional unit, and assessment methodology.

2.2.1 Product Description

The LPT bracket on a Boeing 767 provides mounting and support for mechanical components within aircraft engines and is subjected to various compressive and tensile loads. This bracket is part of the cooling manifold located on the LPT assembly. This bracket is made from an Inconel 718 super alloy by computer-numerical-control (CNC) machining methods from a solid piece of Inconel 718 bar stock, and the finished part weighs 0.122 kg. There are twelve of these brackets per engine and two engines per 767 aircraft. The traditionally manufactured LPT bracket design has been qualified for use on aircraft. (See Figure 12.)

Figure 12: Traditionally manufactured LPT bracket

The AM-produced LPT bracket is produced from Inconel 718 powder on a powder-bed fusion 3D printer (Figure 13) and weighs 0.059 kg. Note that the additive LPT bracket is a new design and has not been qualified for use and is not actively being used on aircraft. To ensure the functional performance of the current additive design, a thorough analysis using finite-element analysis (FEA) was conducted for tensile and compressive loads of 300 pounds and engine operation frequency of 180 hertz, and results showed that it is equivalent to that of the original LPT bracket. The additive LPT bracket is meant to be a direct replacement for the traditionally manufactured LPT bracket that would not require any change in inspection frequency or maintenance.

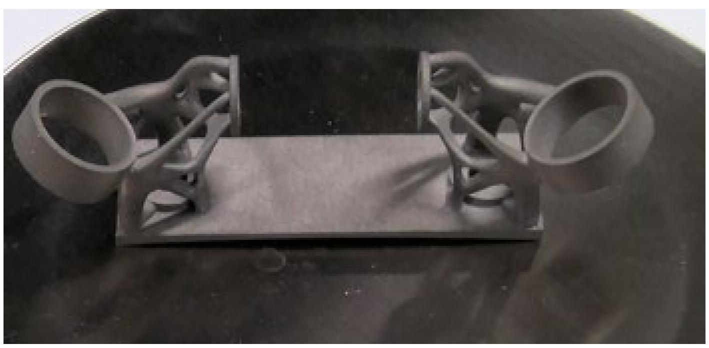


Figure 13: AM-produced LPT bracket

Figure 14: Side-by-side comparison of the traditional and additive LPT brackets

2.2.2 Functional Unit

In Phase 1 of this study, the functional unit used to compare the life cycle impacts of a traditionally manufactured bracket to an AM-manufactured bracket is one bracket.

In Phase 2, the functional unit used to compare the impact of the bracket weight on the airplane fuel use will be the weight difference between 24 brackets of each configuration, and the calculated impact that this weight difference has on fuel use assuming the Boeing B767 aircraft lifetime of 125,000 flight hours. At an average speed of 746 km/hr (based on Boston to London and return travel times for a round-trip flight), the lifetime flight distance is 93.3 million km.

2.2.3 System Boundary

The system boundary for this study includes the cradle-to-grave life cycle of the bracket from the raw material extraction to the bracket end-of-life phase and all steps in between, which include material processing, manufacturing of the brackets, along with related transportation and packaging activities. (See Figure 15.) The gate is considered the point where the finished product is on the loading dock ready for shipping to the customer. Each of the processes in the system boundary will be discussed in more detail in the following sections.

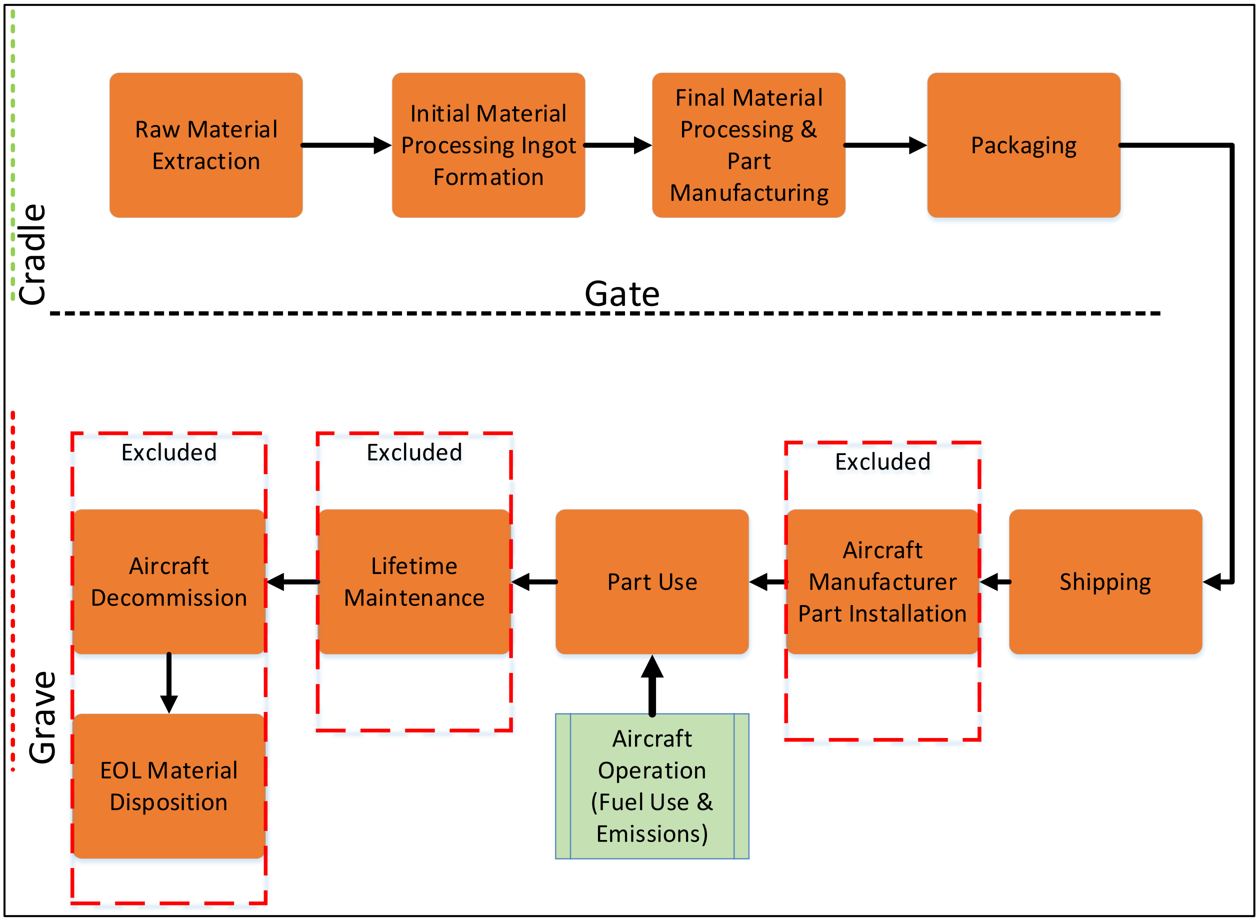


Figure 15: Cradle-to-grave system boundary

2.2.4 Boundary Exclusions

Materials recovered and recycled during this life cycle are credited to the subsequent life cycle and not counted in this life cycle. Overhead energy at the manufacturing locations was not considered. Also excluded were part installation on the aircraft and part maintenance. It is also assumed that the brackets will be recovered at the end of their lives for recycling and reuse, which is accounted for in the next lifecycle.

2.2.5 Cut-off Criteria

An environmental cut-off criterion has been applied in this analysis where any materials or energy that constitute less than one percent of the total may be excluded from this analysis. Any data that is neglected or rejected outside of the system boundaries is justified with individual explanations in Section 4.10, "Assessment Assumptions."

2.2.6 Limitations

The results of this assessment should not be considered the only source of environmental information with respect to the identified products and processes. As is common with all LCA studies, there are limits to data quality, especially for the production of upstream materials where information may vary widely between company, location, and data source. The LCIA results are relative expressions and do not predict impacts on category endpoints, the stating of thresholds, safety margins, or risk.

The data used in this study is representative of the process provided by AMGTA for additive and traditional manufacturing methods. No primary data for the production of the Inconel material is available; therefore, assumptions were made in regards to energy consumption based on published studies and use of surrogate data for similar material.

Table 2: Limitations

Limitation ID	Limitation Description
1	Production energy mix may be different due to changes in manufacturing location.
2	Inconel 718 powder production energy and emissions are not well documented, as is data for similar materials and processes used.
3	Data is only representative of the processes provided by AMGTA.
4	Traditional manufacturing data could not be verified.

2.2.7 Allocation Procedures

No manufacturing operations are shared between the defined traditional and AM system in this study. Other products are not considered in this study; allocation of process inputs and resultant impacts are therefore not items of concern.

Allocation of capital equipment and overhead energy were not considered for this study. It is assumed that the manufacture of these brackets by either facility is a very small portion of the overall operations and relatively similar by comparison, therefore negligible.

The size of the traditional manufacturing facility is approximately 31,000 ft^2, and that of the additive facility is approximately 50,000 ft^2. It can be assumed that any single process or piece of equipment occupies less than 200 ft^2 for the manufacture of the LPT bracket by either facility. This would amount to less than one percent of the overall facility square footage.

For end of life allocation, it is assumed when the Boeing 767 aircraft is retired that the LPT brackets would be recovered for recycling, and therefore, these impacts would be allocated to the next lifecycle.

2.3 Modeling Methodology

2.3.1 Overview

AM of parts offers the ability to optimize part designs and reduce material use while providing comparable functionality to those produced using traditional manufacturing methods. AM can generate features that are not achievable or that may be too costly to do through traditional methods. The processes used to create the AM and traditional parts were used to create the models in SimaPro. The models are based on measured energy consumption along with material inputs and outputs.

2.3.2 Traditional Manufacturing

For this study, Innovative, a traditional manufacturing machine shop, was contracted by AMGTA to manufacture an LPT bracket and collect process data. All specifications and requirements for the bracket were provided to the traditional manufacturing shop. A trial run was first conducted using aluminum material to ensure the machining process was accurate, since aluminum is less costly than Inconel 718. For this study, a round bar stock of Inconel 718 was used to produce one LPT bracket by Innovative. CNC lathes and mills were used to remove material to generate the part features. The final part underwent finishing and inspection processes required by the specification. This study considers all processes for traditional manufacturing and is discussed in more detail in the following sections.

2.3.3 Additive Manufacturing

The AM process uses Inconel 718 powder to generate the optimized part having less material and weight. Sintavia is the additive manufacturer responsible for designing and manufacturing the optimized LPT bracket. The additive process replaces the traditional, subtractive machining process. For this study, Sintavia was able to produce 42 brackets on a single build-plate at the same time. After the build, the parts go through a stress-relieving process before removal from the plate. Once removed from the plate, they follow a similar path of finishing and inspection that the traditional LPT bracket undergoes.

3 Life Cycle Inventory

3.1 Inconel 718 Alloy Material

Background

Inconel 718 is a Ni-Fe (nickel-iron-based) super alloy that has been an important part of the gas-turbine industry, including aircraft and land-based engines, since it was discovered in 1963.[4] Inconel 718 is comprised of a number of different elements (Figure 17). Combining these elements and refining the material can be energy-intensive.

The melting process is one such area where energy use is of interest. Typically, Inconel 718 is melted according to one of the following three practices:

- vacuum induction melt (VIM) + electroslag remelt (ESR)
- vacuum induction melt (VIM) + vacuum arc remelt (VAR)
- VIM+ESR+VAR[4]

The liquid metal is then poured into molds and solidified to form the ingots. For this study, the material was produced using the vacuum-arc remelt method. After the ingot is formed, additional processing may be required, depending on the desired application and material properties.

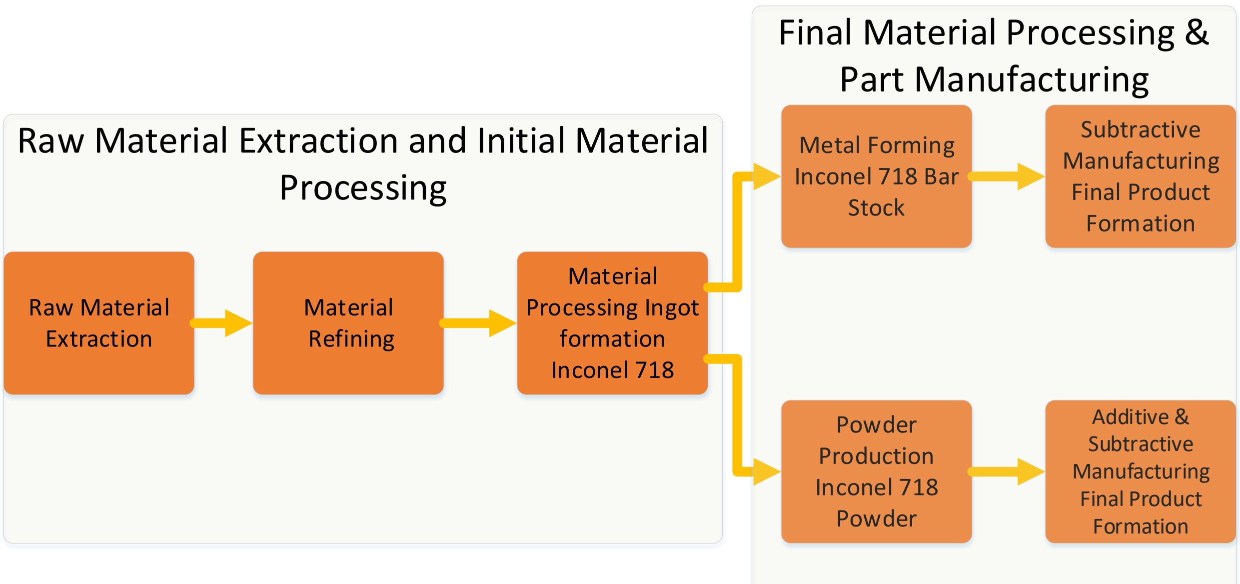


Figure 16: Shared and divergent cradle-to-gate life cycle phases for AM and traditional machining

ATI Specialty Materials-4374 Lancaster Highway,Richburg, SC 29729 US

Batch - 229969 Heat - M9L31 Ingot - 1

CHEMISTRY

Sample Source			Heat Avg
Test Facility			ATI Monroe Operations
Elements	UOM	Method	Average
C	%	CS	0.03
Mn	%	XRF	0.07
Si	%	XRF	0.06
P	%	XRF	0.008
S	%	CS	<0.0003
Cr	%	XRF	17.95
Ni	%	XRF	53.76
Mo	%	XRF	2.89
Nb	%	XRF	5.42
Ti	%	XRF	1.00
Al	%	XRF	0.48
Co	%	XRF	0.23
B	%	OES	0.004
Cu	%	XRF	0.04
Fe	%	XRF	Bal

Remarks:
CS = Combustion/IR Detection
OES = Spark Optical Emission
XRF = X-Ray Fluorescence

Figure 17: Chemical composition report for bar stock

The final Inconel 718 product is seen in Figure 18 as received by the part manufacturer. The material manufacturer specifies that this bar stock needs to be hot-rolled and heat-treated after primary melting through VIM and secondary melting through VAR, as seen in Figure 19.

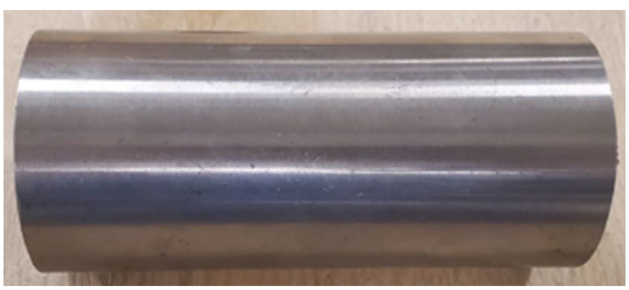


Figure 18: Inconel 718 bar stock for traditional manufacturing

ATI Specialty Materials
4374 Lancaster Highway,
Richburg, SC 29729
US

CERTIFICATE OF TEST
Cert No.347595 Rev.1

Tina K. Colettiles
Certification Auditor
Date : October 31, 2019

Batch - 229969
Heat - M9L31
Ingot - 1

Customer Name & Address	Purchase Order No	Purchase Order Line No	Sales Order No	Sales Order Line No
Rolled Alloys PO Box 310 125 West Sterns Road Temperance MI 48182 US	0175299-STR	2	117635	2.1

Size (in)	Cross section	No Pcs	Weight (lbs)	Alloy
1.7500	Round	25	3,010	ATI 718™ Alloy

Specifications

Spec Name	Rev	Compliance Condition
AMS 5662	N	Compliant
AMS 5663	N	Capability

As Shipped Condition

Heat Treat	Heat Treat Cycles	Hot Work Type
Solution Annealed	Heat To 1750 F Hold 1 Hr(s) Air Cool	Rolled

Surface Finish
Centerless Ground
Remarks:
Cold Finished

Melt Method Details

Primary Melt	Facility	Address
Vacuum Induction Melt	ATI Monroe Operations	2020 Ashcraft Avenue, Monroe, NC 28110-5030 US

Remelt	Facility	Address
Vacuum Arc Remelt	ATI Monroe Operations	2020 Ashcraft Avenue, Monroe, NC 28110-5030 US

Conversion Method Details

Conversion Type	Facility	Address
Rolling	ATI Richburg Operations	4374 Lancaster Highway, Richburg, SC 29729 US

Figure 19: Heat-treatment and metal-working report for bar stock

3.1.1 Material-Modeling Methodology in SimaPro

The Inconel 718 alloy does not exist as a standalone material in the Ecoinvent database; therefore, the material was built using various available data points for compositional elements and energy consumption during processing. This was accomplished using the existing elemental components of Inconel 718, available in the Ecoinvent 3.8 database to create a model in SimaPro, in the specific ratios as reported in the supplier material test report Figure 17. The primary materials include nickel, chromium, and iron, which make up over 85 percent of Inconel 718 and are available in the Ecoinvent 3.8 database. Additionally, the appropriate conversion processes were selected that are representative of the energy inputs required to create the final Inconel bar stock received by the part manufacturer.

To simplify the SimaPro Inconel material model, trace elements that contributed less than 0.1 percent to the Inconel-718 composition were not included in the analysis. It is assumed that the contribution from these elements results in impacts that are well below the cut off threshold. Table 3 shows the elements that compose Inconel 718, detailing their percent contribution along with those that were included in the model. It is important to note that simplifications and assumptions applied to this model might affect the overall results and that with better process and material data, results might change.

Table 3: Inconel 718 Model

Chemistry Symbol	Name	Report Value percent	Ecoinvent Material	Included in Model Y/N
C	Carbon	0.03	N/A Below 0.1 percent Threshold	N
Mn	Manganese	0.07	N/A Below 0.1 percent Threshold	N
Si	Silicon	0.06	N/A Below 0.1 percent Threshold	N
P	Phosphorus	0.008	N/A Below 0.1 percent Threshold	N
S	Sulfur	0.0003	N/A Below 0.1 percent Threshold	N
Cr	Chromium	17.95	Chromium, at regional storage/RER U	Y
Ni	Nickel	53.76	nickel, 99.5 percent, at plant/kg/GLO	Y
Mo	Molybdenum	2.89	molybdenite, at plant/kg/GLO	Y
Nb	Niobium	5.42	ferroniobium production, from pyrochlore concentrate, 66 percent Nb BR	Y
Ti	Titanium	1	Titanium {GLO}| titanium production | APOS, U	Y
Al	Aluminum	0.48	Aluminum, primary, at plant/RER U	Y
Co	Cobalt	0.23	cobalt, at plant/kg/GLO	Y
B	Boron	0.004	N/A Below 0.1 percent Threshold	N
Cu	Copper	0.04	N/A Below 0.1 percent Threshold	N
Fe	Iron	18.0577	Pellets, iron, at plant/GLO U	Y
		Total percent		
	Included	99.7877		
	Excluded	0.2123		

For the elements that are included, a survey of the Ecoinvent 3.8 database was conducted to identify the appropriate materials from what is available. In many instances, the elements exist in various forms and require careful evaluation to select the ones that fit best, as explained below.

- Chromium, at regional storage RER/U, is a unit process that produces chromium designed solely for use as an alloying element in super alloys containing nickel and chromium.
- Nickel, 99.5 percent, at plant/kg/GLO, is the process for producing nickel that can be used as an intermediate product or as a raw material for manufacture of stainless steels and alloys.
- Molybdenite, at plant/kg/GLO, is used as an input material for the alloying of steel and is assumed to serve a similar purpose for nickel alloys.

- Ferroniobium production, from pyrochlore concentrate, 66 percent Nb BR process description does not provide description on end use.
- Titanium {GLO}| titanium production | APOS, U is the process for making primary titanium material and is assumed to be a direct input to the Inconel process.
- Aluminium, primary, at plant/RER U is the process for making primary aluminum material and is assumed to be a direct input to the Inconel process.
- Cobalt, at plant/kg/GLO U, is assumed to be representative of the input material to make Inconel 718.
- Pig iron, at plant/GLO U, is assumed to be representative of the input material to make Inconel 718.

Material selection in the Ecoinvent 3.8 database typically includes the embodied energy and emissions for mining of the raw ore, along with processing of that ore into the specific material. Figure 20 shows the SimaPro model that was built based on available materials in the Ecoinvent database and corresponding ratios from the material specification. The data sheet in Figure 17 lists iron as making up the balance of the material composition; to make up for material not included due to the cut-off limit, an iron balance of 0.02123 kg was added to complete the 1 kg of the Inconel material.

Inputs from technosphere: materials/fuels	Amount	Unit
Chromium, at regional storage/RER U	0.1795	kg
Nickel, 99.5%, at plant/GLO U	0.5376	kg
Molybdenum trioxide {GLO}| production | Cut-off, U	0.0289	kg
Ferroniobium, 66% Nb {BR}| ferroniobium production, from pyrochlore concentrate, 66% Nb | Cut-off, U	0.0542	kg
Titanium {GLO}| titanium production | Cut-off, U	0.01	kg
Aluminium, primary, at plant/RER U	0.0048	kg
Cobalt, at plant/GLO U	0.0023	kg
Pig iron, at plant/GLO U	0.1805	kg
Pig iron, at plant/GLO U	0.02123	kg

Figure 20: SimaPro Inconel 718 Model for chemical composition

To complete the material production, an appropriate conversion method and processing is required. Since the Ecoinvent database does not have a specific process for Inconel 718, surrogate representative processes were selected. It is assumed that this processes will be representative of the alloying processes used for Inconel. Primary data of this process would be required to better understand the inputs and outputs to the Inconel alloying process.

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution
Iron-nickel-chromium alloy, at plant/RER U	1	kg	Undefined
Hot rolling, steel/RER U	1	kg	Undefined

Figure 21: SimaPro Inconel 718 production process

Ecoinvent 3.8: Hot-rolling, steel/RER U

- Included processes:
  - scarfing, grinding heating, descaling, rolling, and finishing
  - semi-closed water circuit with water treatment plant
  - *Does not include the material being rolled.*
- Remark:
  - To achieve greater toughness, shock resistance, and tensile strength, the raw-steel-production outputs cast ingots, slabs, billets, and beam blanks are hot-rolled to long, flat, or semi-finished products.
- Geography:
  - Dataset is representative of the European Union.
- Technology:
  - average technique for European Union
- Assumption:
  - One-hundred percent of heating is achieved with natural gas.
  - Furnaces of about 10 MW are approximated by furnace as "> 100 kW."

Ecoinvent 3.8: Iron-nickel-chromium alloy, at plant/kg/RER

- Included processes:
  - transports of scrap metal and other input materials to electric arc furnace (EAF)
  - steel-making process
  - casting
- Remark:
  - Original process, which is excluded from the model, used in this study.
  - Class I nickel is used as a nickel input and ferrochromium (68 percent Cr) as a chromium input is used.
  - Scrap is only used as iron-bearing input.
  - No nickel or chromium input from the iron scrap is assumed.
- Formula:
  - X10NiCrAlTi 32-20
- Geography:
  - Data representative of EAF plants in the European Union.
- Technology:
  - EAV process for stainless steel used as approximation for the production of high iron-nickel-chromium alloys.
  - European Union technology mix for EAF process (mainly furnace with fourth hole, partly with additional evacuation of building atmosphere).

For this process, the nickel and ferrochromium inputs were removed and the Inconel material was used in its place, along with the specific material manufacturing location energy mix.

The final step is a heat-treating process where 2.03 kWh are applied to raise the temperature of Inconel, which has a specific heat of 5686 l/(kg °C) 1680 °F (70–1750 °F) and a mass of 1.373 kg.

3.1.2 Additive-Powder Process

Inventory data for Inconel 718 powder are not documented as well as traditional bar stock materials. Data from published literature is used for powder production, post-processing energy and emissions. Additive feedstock materials require additional process and preparation that may result in additional environmental impacts.[5] The general process for manufacture of the additive powder can be seen in Figure 22.

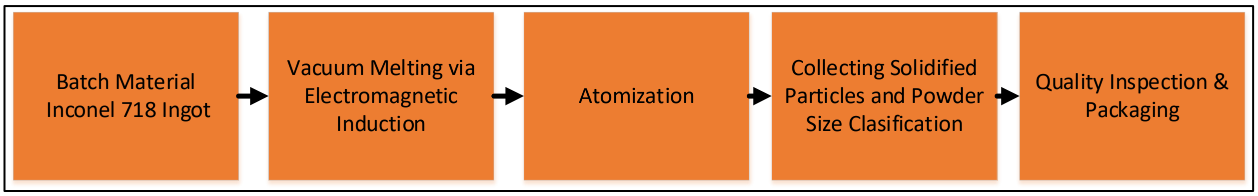


Figure 22: Powder-production process

The additive powder used for the LPT bracket is TruForm™ 718 Metal Powder from Praxair Surface Technologies.[6] The powder-production method used is vacuum-induction melting with argon-gas atomization. The specific embodied energy and emissions for this process are not well documented. Several publications provide estimations for similar materials that can be used as a surrogate for the actual process.

A 2007 study investigated the environmental aspects of laser based and conventional tool and die manufacturing.[7] The study's results provide an estimation for the atomization of tool steels to achieve a powder that reaches an energy value of 1 MJ/kg (0.28 kWh/kg), excluding the melting operation. The authors also indicate that the melting process is approximately 5.45 MJ/kg (1.51 kWh/kg).

For this study, a value of 1.0 MJ/kg (0.277 kWh/kg) of energy is applied for the gas-atomization process. For the re-melt process of the material going into the atomization process, a conservative value of 7.2 MJ/kg (2.0 kWh/kg) is applied.

It is important to note that it is unknown a) if all powder-production steps are included within the range of energy values selected and how well they apply to Inconel, and b) the overall process efficiency in converting Inconel into powder. Better data from the Inconel process will most likely change the results.

Figure 23: Inconel TruForm 718 powder

3.2 Traditional Bracket Life Cycle Inventory

Primary life cycle inventory data was provided for the traditional manufacturing processes and the full inventory can be found in Appendix A: "Data Sources." It is unknown if any additional heat treatment is applied to the finished traditional LPT bracket beyond the heat treatment that was already applied to the raw material the part was machined from. The heat-treatment applied and modeled is discussed in Section 3.1.1.

3.2.1 Traditional Bracket Manufacturing

Traditional manufacturing data was provided by Innovative.[8] Innovative was contracted by AMGTA to manufacture the LPT bracket by the traditional methods. The traditional process flow is shown in Figure 24.

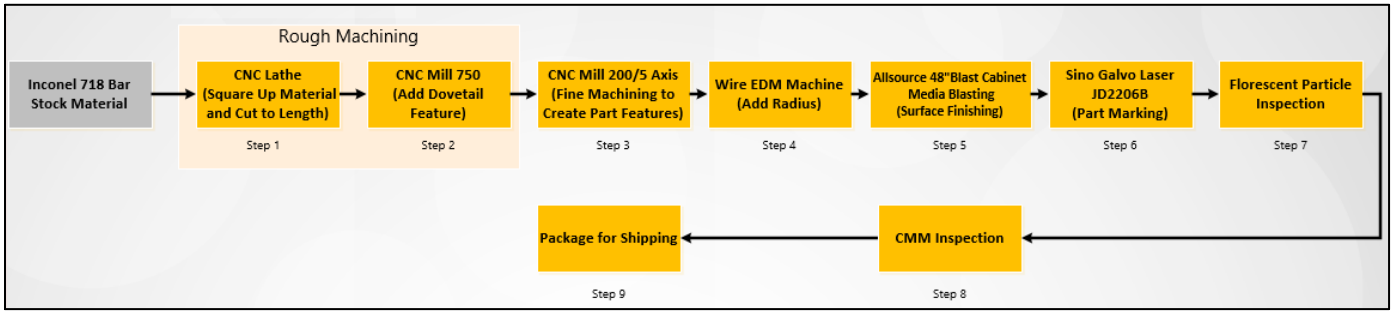


Figure 24: Traditional manufacturing process

There are nine discrete process steps involved in the traditional manufacturing of the LPT bracket. This covers the point where the material is received to where the final product is packaged and ready for shipping to the customer, shown in Figure 24.

3.2.2 Machining-Process Background

The following four primary machining operations are involved in the traditional manufacturing process:

1. Rough machining: Square up material and cut to length.
2. Rough machining: Add dovetails feature(s).
3. Fine machining: Create part features.
4. Wire electronic discharge machine (EDM) finishing: Add radius.

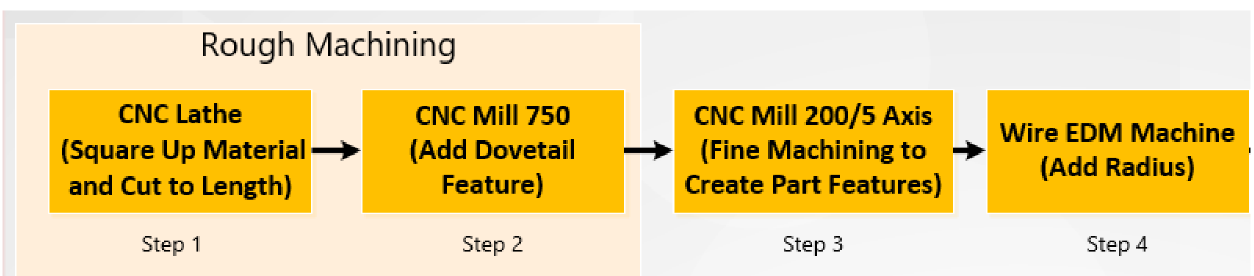


Figure 25: Conventional Manufacturing Process

The primary data collected by Innovative recorded total time spent and the total mass of material removed. Innovative also provided the rated power for each process based on equipment specifications, which can be found in Table 4. These machines were not metered and actual machine-energy was not measured during part-processing.

Table 4: Specifications for Conventional LPT-Bracket Process Equipment

Machine	kilovolt-amperes (kVA)	amperes (A)	voltage (V)	kiloWatts (kW)
Doosan DNM 750	43	125	220	27.5
Doosan Puma 2600y	47	123	220	27.06
Primary Operation Doosan 200/5 Axis	32	87	220	19.14
Wire EDM	15	40	220	8.8

Table 5 provides the process-specific runtime and energy consumption estimates provided by Innovative based on equipment specifications along with part weight and mass of material removed for each process.

Table 5: Conventional LPT-Bracket Process Characteristics

Operation Description	Runtime Hours	Energy Intensity Kilo Watthours (kWh)	Part Weight (kg)	Weight of Material Removed (kg)
Lathe Operation Face Material Doosan Puma 2600y	0.17	4.5	**1.3725**	**Negligible**
Rough Machining Dovetail Doosan DNM 750	0.25	4.8	**0.9403**	**0.4322**
Primary Operation Fine Machining (Create Part Features) Doosan 200/5 Axis	NA	NA	**0.1650**	**0.7753**
Wire EDM Radius Cut	1.00	8.8	**0.1293**	**0.0357**

An energy-intensity value is calculated based on the process-specific energy and mass removed (shown in Table 6 as "energy per unit mass"). This serves as the basis for comparison and validation against existing published data for similar processes.

Table 6: Calculated Energy Intensity per Process

Operation Description	Energy Intensity Kilo Watt-hours (kWh)	Weight of Material Removed (kg)	Energy Intensity of Material Removed (kWh/kg)	Energy Intensity of Material Removed (MJ/kg)
Lathe Operation Face Material Doosan Puma 2600y	4.5	**Negligible**	NA	NA
Rough Machining Dovetail Doosan DNM 750	4.8	**0.4322**	15.9	57.3
Primary Operation Fine Machining (Create part features) Doosan 200/5 Axis	NA	**0.7753**	NA	NA
Wire EDM Radius Cut	8.8	**0.0357**	246.3	886.7

3.2.3 Step 1: CNC Lathe

The first step in the machining process, as shown in Figure 25, is the CNC lathe. This is a roughing process where the bar stock material is cut to length and squared off. The manufacturer indicated that during this process only 0.07 in. of material was removed from the part and considered this value to be minimal and non-invasive to the overall process.

3.2.4 Step 2: CNC Mill 750

The second step in the process used the CNC Mill 750 to make a dove-tail feature for mounting the bar stock in a fixture in the fine-machining process step. Figure 26 shows the material with completed dove-tail feature.

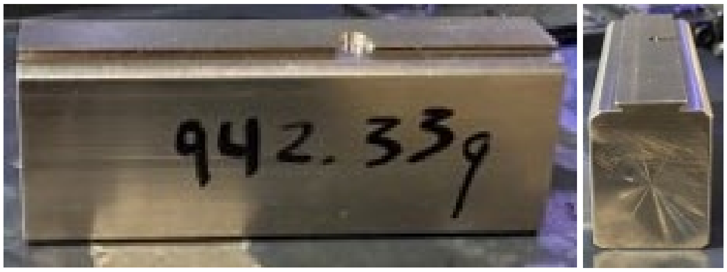


Figure 26: Dove Tail Feature

3.2.5 Step 3: CNC Mill 200/5 Axis

The third step is considered to be the primary manufacturing process for creating a majority of the part features. A complete list of the tooling used for this process was provided by Innovative, shown in Figure 27.

Date: 1/25/2022 6:21:33 AM	Pages: 1	Filename: Y:\DOOSAN5AXIS\11091\BRKT2.NC

```
O0001
(BRKT2)
(T17|1/2 IMCO 7 FLT. ENDMILL |H17|XY STOCK TO LEAVE - .005|Z STOCK TO LEAVE - .005)
(T11|3/16 FLAT ENDMILL |H11|XY STOCK TO LEAVE - .005|Z STOCK TO LEAVE - 0.)
(T10|1/4 CARBIDE DRILL |H10)
(T12|3/8 FLAT ENDMILL |H12|D12|WEAR COMP|TOOL DIA. - .375)
(T23|1/2 BULL ENDMILL 0.0625  RAD |H23|D23|WEAR COMP|TOOL DIA. - .5)
(T7|12.5MM CARBIDE DRILL |H7)
(T9|1/4 BALL ENDMILL |H9)
(T14|3/32 BALL ENDMILL |H14)
(T13|1/16 BALL ENDMILL |H13|XY STOCK TO LEAVE - .005|Z STOCK TO LEAVE - 0.)
(T8|1/8 FLAT ENDMILL |H8|D8|WEAR COMP|TOOL DIA. - .125)
```

Figure 27: Tooling list for primary machining operations

The primary machining process was performed by Innovative on the Doosan 200/5-axis CNC mill. The spindle and coolant pump motors are the major energy consumers during the machining operation. A detailed review of the Doosan 200 / 5-axis product specification found that the maximum continuous power is rated at 11 kW (not 19.14 kW). Further investigation of the machine-tooling used to create the part, such as drill bits and small end mills that are less than one quarter of an inch in size, indicated that much of the time spent machining would be done at less than maximum continuous power. This investigation determined that the machine-rated power is not representative in this particular case study and that further study is necessary. (See Section 4.2.6 for additional discussion.)

Inconel is a difficult material to machine, often requiring multiple tool bits throughout the process. The tool bits are modeled as a consumable in the LCA model. It was reported that three drills were replaced during the manufacture of the example part, whereas other tooling bits can last over the course of machining a few parts. This study assumed that 0.4 kg of tooling was required per part produced. A silicon carbide material was selected for the tooling material.

Table 7: CNC Tooling Material

SimaPro Input	Amount	Unit	Method
Silicon carbide, at plant/RER U	0.4	kg	Calculated

Mill machines use coolant which is injected from a 55-gallon drum that is fed with water to create coolant for the milling machines. However, the drum lasts approximately two months and is shared between nine machines. All coolant is disposed of in a large container and an outside company pumps it and disposes of it safely. Since coolant utilization was not provided, an assumption was made that these machines operate 25 days per month, 16 hours per day (two shifts), and nine machines utilizing one 55-gallon drum of coolant. It is assumed the cutting coolant is mineral-oil based.[9] For the operation of the cutting machines, it was calculated that 0.523 kg of coolant was used per part. Waste coolant is assumed to go to hazardous-waste incineration.

Table 8: CNC Coolant

SimaPro Input	Amount	Unit	Method
White mineral oil, at plant/RNA	0.523	kg	Calculated
Disposal, used mineral oil, 10 percent water, to hazardous waste incineration/CH U	0.523	kg	Cutting fluid waste

Waste material at Innovative is sorted by material type and taken to a recycling center. Inconel is extremely valuable and highly recyclable; therefore, all removed material has been modeled as being recycled using the cut-off method. Recycling will be allocated to the subsequent life cycle. There is potential that a small amount of material is not recoverable and would be disposed. This amount is considered to be insignificant and below the environmental cut-off, therefore, not considered in this study.

Compressed air is used to blow off parts during operation, but it is very minimal. Operators spend 1–2 seconds clearing coolant off of parts in general.

SimaPro Input	Amount	Unit	Method
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	1.26	Cubic foot	Calculated 2 seconds 38 cfm @125 psi

3.2.6 Machine Energy Background Research for Steps 1–3

Given the significant impact of the Doosan 200/5-axis CNC mill and the high uncertainty in energy-use calculation based on the machine ratings, a literature search was conducted. This sought to identify other publicly available data sources for the energy consumption of machining Inconel 718 in order to compare it with Innovative's primary data.

One study was found that investigated the variation of process parameters, including cutting speed, feed per tooth for mill bits, and radial depth of cut (DoC) along with cooling-pump operation to determine the effects on the overall machine specific energy.[10] The authors looked at cutting with and without the cooling pump active, which is described as flood- and dry-cutting to determine the effects on the machine specific energy.

End-milling was performed on a Cincinnati Arrow 500 CNC milling machine under dry and flood conditions. This machine tool has a Grundfos CHK2-60/6 A-W-A-CVBV coolant pump. The machine and spindle powers were directly measured using a Fluke Norma 5000 power analyzer.[10]

A 2018 study by Z. Y.Liu et al. provides a range of machine specific energy for the process parameters selected. Flood-cutting shows higher energy use across all process-parameter variations, which can be attributed to the cooling-pump operation. The machine specific energy reported for various process parameters ranged from a minimum of 39.0 kWh/kg up to a maximum of 94.38 kWh/kg with a mid-range of 58.0 –71.0 kWh/kg. For example, if specific energy for machining is 2000 J/mm^3 and an assumed density of 8180 kg/m^3, results in an energy intensity of 67.916 kWh/kg material removed.

Table 9: Inconel 718 Density

Inconel 718 Density	8.18E-06	kg/mm^3

Table 10: Machine Specific Energy Consumption According to Liu et al. 2018 Study[10]

Process Parameters	Flood-Cutting, Cutting Speed 80 (m/min)	Flood-Cutting, Cutting Speed 60 (m/min); Feed per tooth 0.15 (mm/tooth)	Flood-Cutting; Radial DoC 0.40 (mm)	Flood-Cutting; Radial DoC 0.30 (mm)	Units
Machine Specific-Energy Range	39.05	57.73	71.31	93.38	kWh/kg
	140.59	207.82	256.72	336.19	MJ/kg

A 2017 study by D. J. Brown conducted a similar experiment as Liu et al. for flood and dry milling of conventional and additively deposited Inconel 718 and potential effects the material properties have on energy. It found the total maximum specific energy consumption to be 1,664.87 J/mm^3 of material removed. [11] This translates to approximately 56.5 kWh/kg of energy per mass of material removed. The minimum value reported was approximately 49.82 kWh/kg. The flood-cutting energy of 56.5 kWh/kg is in close agreement with the flood-cutting energy of 57.7 kWh/kg that Lui et al. observed. Therefore, it can be concluded that the values from the Lui et al. study are representative of an industry average and range.

Table 11: Machine Specific-Energy Consumption According to 2017 Brown Study[11]

Process Parameters	Dry-Cutting of SLMed IN718 material	Flood-Cutting of SLMed IN718 material	Units
Machine Specific Energy Range	49.82	56.54	kWh/kg
	179.34	203.55	MJ/kg

The model developed in this LCA takes Liu et al.'s machining-energy values as an accurate representation of the industry standard rate for machining Inconel 718 (as listed in Table 12). The resulting model based on this average value assumes a uniform distribution between the maximum and minimum values for the uncertainty analysis.

Table 12: Energy-value range used in analysis

	Min	Average	Max	Units
Machine Specific Energy Range	39.05	57.73	93.38	kWh/kg
	140.59	207.82	336.19	MJ/kg

3.2.7 Step 4: Wire EDM

The wire-EDM process is the final step of machining, completing the part by adding a radius to the bottom. Innovative reported that this operation took approximately one hour. Wire-EDM machining was modeled in SimaPro and shown in Table 13.

Table 13: SimaPro Wire-EDM Model

SimaPro Input	Amount	Unit	Method
Brass, at plant/CH U	0.091	kg	Measured
Wire drawing, copper/RER U	0.091	kg	Measured
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	162	Cubic foot	Calculated(162 cu ft/hr)2.7 cu.ft./min. @ 71~100 psi
Electricity, low voltage, production South Carolina	8.8	kWh	Measured

3.2.8 Media-Blasting (Surface-Finishing)

The surface-finishing process uses abrasive media to remove any burrs and sharp edges on the part. The process uses aluminum-oxide abrasive and compressed air. It is assumed the used media will go to a landfill.

Table 14: Media-blast process Inputs

SimaPro Input	Amount	Unit	Method
Aluminium oxide, at plant/RER U	0.227	kg	Calculated: last Media: Innovative estimates using half of a 50 pound bag on 50 parts, this equates to 0.5 lbs/part or 0.227kg/part
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	30	Cubic foot	Calculated: 15 cfm at 80 psi 2 minute process
Process-specific burdens, inert material landfill/CH U	0.227	kg	Aluminum oxide media waste

3.2.9 Part-Marking

Primary energy data was not provided for when parts are marked with identifying criteria. This process takes approximately one minute to perform. The part-marking tool used is a Sino Galvo Laser JD2206B. Product specifications indicate that there could be a 20–30-W laser, but specific details were not provided.

Ecoinvent has a laser-machining process for a 30-W power laser for one hour of operation. This was chosen as a surrogate for the part-marking process for the one minute of operation.

3.2.10 Florescent-Particle Inspection (FPI)

This process was performed by a contract vendor. The finished part is shipped to a local lab for florescent-particle inspection (FPI), then shipped back to the manufacturer with a test report. Transport is modeled for this processes, where round trip distance is 13.2 km using a transport van. Primary data was not collected for this process. One reference reported that the FPI inspection process used 0.20 kWh of energy.[12] This assumption was applied to the model. No other inputs were accounted for in this process.

3.2.11 Coordinate-Measuring Machine (CMM) Inspection

The coordinated-measuring machine (CMM) inspection process is performed to ensure the LPT bracket features meet the required specifications and tolerances. This process is also performed for the additive LPT bracket. Since the CMM primary energy data was directly measured for the additive LPT bracket at Sintavia and the CMM primary-energy data was estimated for the machined LPT bracket, the measured CMM energy for the additive bracket was applied to both manufacturing methods. The only difference will be the energy mix applied due to different manufacturing locations.

Table 15: CMM Inspection Input

SimaPro Input	Amount	Unit	Method
Electricity, low voltage, production South Carolina	0.1786	kWh	Using primary data from the AM process; it is assumed that this will be the same process for measuring and with the AM.
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	5	Cubic foot	Calculated: Estimate 10 seconds to pressurize the CMM with negligible losses

3.3 Additive Bracket Inventory

This analysis considers a LPT bracket manufactured by an EOS M400 DMLS (direct metal laser-sintering) printer from Inconel 718 powder. Primary life cycle inventory data was collected by Sintavia for the additive manufacturing processes and the full inventory can be found in Appendix A: “Data Sources.”

3.3.1 Additive Bracket Manufacturing

For the additive LPT bracket, Sintavia staff collected the primary data for each process step shown in Figure 28. A summary of energy use is represented in Table 17. It is standard practice to maximize the material utilization during manufacturing and it is not cost effective to 3D print only one part at a time.

Since the EOS M400 chamber volume can manufacture 42 LPT brackets at a time, all values for material use are normalized to one LPT bracket assuming this level of utilization.

The AM process follows 13 discrete steps (Figure 28). These steps include the primary additive process to build the part, the subtractive processes to generate final features, and the finishing and inspection processes. Each of these processes will be described in more detail in the following sections.

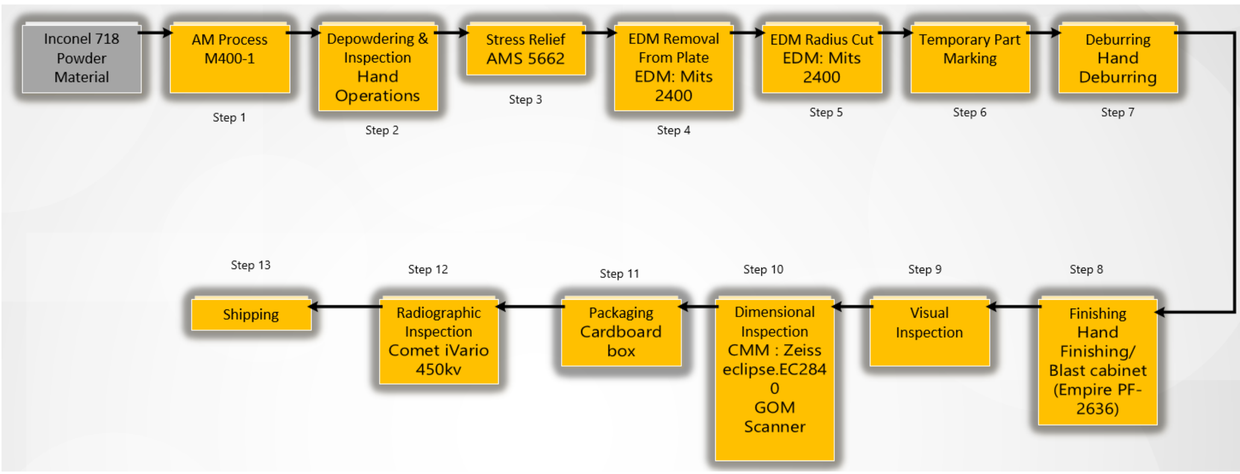


Figure 28: Additive-manufacturing process flow

For the additive process, the Inconel 718 powder feedstock was weighed and then fed into the EOS M400. Fifty seven kg of Inconel 718 powder were used to build 42 parts. Most of the unused material was recovered for reuse due to the high reusability of nickel-based alloys.

Consideration needs to be made for the total amount of material required for the build volume of one part (Figure 29). This includes the powder that is sintered into the solid part and loose surrounding powder that is required to build the part, but will later be recovered. This required powder volume will be the basis for the additive input material. Based on the 57-kg input for 42 parts, the amount comes to approximately 1.357 kg of powder. This value will be used for all transport activities and material production for the additive powder.

The additive parts are manufactured on a metal build-plate with a mass of 80 kg. Sintavia reported that a single plate was used for approximately five build cycles before being replaced. The input assumption for the build-plate is in Table 16.

Table 16: Additive Build Plate Input

SimaPro Input	Amount	Unit	Method
Chromium steel 18/8, at plant/RER U	0.381	kg	Surrogate for the stainless steel build-plate. 1 build-plate is 80 kg for 42 brackets (80/42)=1.9047 one build-plate is good for up to 5 build sequences.

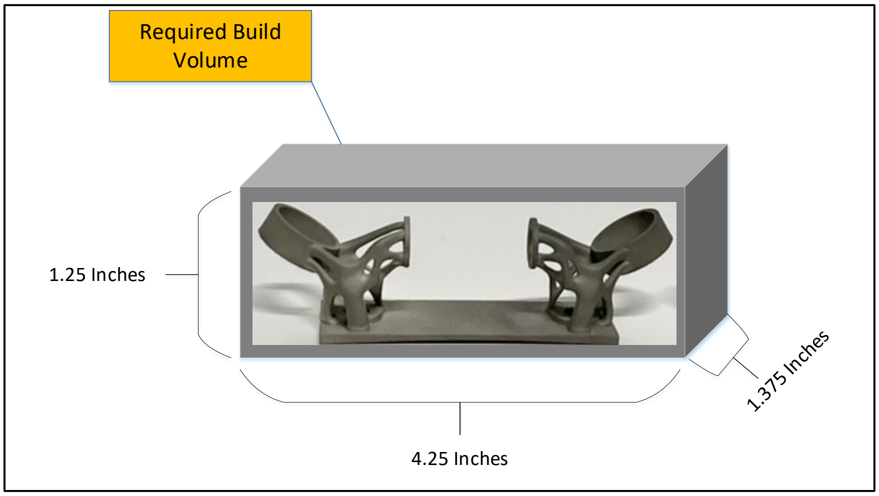


Figure 29: Build-volume requirement

The energy inventory for the main processes is listed in Table 17. These values are normalized to one part from the data provided for the 42-part build.

Operation	Total Energy per part (kWh)
AM Process M400	30.81
Stress Relief	0.5283
Wire EDM from Build plate	1.607
Wire EDM Radius Cut	10.125
Media Blast	0.0750
CMM Inspection	0.179

Table 17: Energy-Consumption Inventory for Additive-Manufacturing Process

3.3.2 Depowdering

Depowdering removes any residual powder not initially recovered after the build. This process uses compressed air and any residual waste powder is discarded.

Table 18: Depowdering Model Inputs

SimaPro Input	Amount	Unit	Method
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	11.42	Cubic foot	Calculated
Process-specific burdens, inert material landfill/CH U	.010952	Kg	Measured

3.3.3 Stress Relief

The additive brackets, while still on the build-plate, are placed into an oven where the temperature is increased to 1950 °F and held for 90 minutes and then let to cool down naturally. During the process, argon in injected into the oven chamber. Values for the argon and electricity use were normalized to the estimated volume of one bracket attached to a build-plate section. It is assumed that multiple build-plates could be placed in the oven at a time.

Table 19: Stress Relief Process

SimaPro Input	Amount	Unit	Method
argon, liquid, at plant/RER U	2.536	kg	Calculated: Total argon used is 16995 Liters over 9 hours, normalized to the volume of 1 bracket 3.375 cu in) Furnace volume is 36 cu ft. Data measured at Sintavia 1 kg of argon is 0.718 Liters
Electricity, low voltage, production Florida	0.5283	kWh	Measured

3.3.4 EDM Removal from Plate and Radius Cut

For the additive LPT bracket there are two EDM operations. The first is to remove the brackets from the additive build-plate and the second is to create the radius feature on the bottom of the part. EDM wire was modeled and shown in Table 20.

Table 20: SimaPro Wire EDM Model

SimaPro Input	Amount	Unit	Method
Brass, at plant/CH U	0.091	kg	Measured
Wire drawing, copper/RER U	0.091	kg	Measured
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	162	Cubic foot	Calculated(162 cu ft/hr)2.7 cu.ft./min. @ 71~100 psi

3.3.5 Temporary Part-Marking

The temporary part-marking process uses a permanent marker to label parts. It is assumed that the markers will be used on many parts and per part impacts are negligible.

3.3.6 Deburring by Hand

Deburring by hand is considered a manual operation and requires no significant input. Waste material is also assumed to be negligible.

3.3.7 Finishing-Media Blast Cabinet

The finishing-media blast cabinet surface finishing process uses abrasive media to remove any burrs and sharp edges on the part. The process uses aluminum oxide abrasive and compressed air. It is assumed that the used media goes to a landfill.

Table 21: Media-Blast Process Inputs

SimaPro Input	Amount	Unit	Method
Aluminium oxide, at plant/RER U	0.7583	kg	Calculated: last Media: 31.85 kg for 42 parts
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	90	Cubic foot	Calculated: 15 cfm at 80 psi 6 minute process
Process-specific burdens, inert material landfill/CH U	0.7583	kg	Aluminum oxide media waste

3.3.8 Visual Inspection

The additive LPT bracket is manually inspected by eye to ensure the parts have been finished adequately. No inputs or outputs are considered for this process.

3.3.9 CMM Dimensional Inspection

The CMM dimensional inspection process is performed to ensure the LPT bracket features meet the required specifications and tolerances. The energy data for the additive LPT bracket was measured by Sintavia.

Note that the additive bracket weight is significantly less than traditionally machined bracket. This is due to the unique design processes that are enabled by the additive or 3D-printing process. The additive bracket at final inspection is only 0.059 kg, less than half the weight of the 0.122-kg machined bracket. Despite being lighter, it still can meet the same dimensional requirements as the machined bracket.

Table 22: CMM Inspection Input

SimaPro Input	Amount	Unit	Method
Electricity, low voltage, production South Carolina	0.1786	kWh	Measured
Compressed air, average installation, >30kW, 7 bar gauge, at supply network/RER U	5	Cubic foot	Calculated: Estimate 10 seconds to pressurize the CMM with negligible losses

3.3.10 Radiographic Inspection

Radiographic inspection uses an isotope or an x-ray tube to create an image. Volumetric inspection detects defects which are not open to the surface, and may not otherwise be detectable. The process energy was measured to be 0.1 kWh. This process is conducted by an outside lab for the additive manufacturer that is located nearby, where parts are transported by van to and from the lab. This transportation is included and 0.000917 ton-kilometers (tkm) is applied, which assumes a 15.45-km round trip.

3.4 Manufacturer Electricity-Grid Mix

The initial electricity grid mixes used for the baseline case of this study were based on the specific part manufacturing locations. The goal of this study, however, is broader than comparing two specific manufacturers and manufacturing locations, and therefore, a sensitivity analysis was performed using a U.S. average grid mix and different manufacturing locations to determine if the differences in manufacturing process can be separated from the grid mix. This is discussed in more detail in the sensitivity section of this report.

Material- and part-manufacturing occurred in three different U.S. states in the baseline case study. Raw material ingredients are processed at ATI Specialty Materials to make the Inconel 718 bar stock located in South Carolina. The traditional manufacturing of the LPT bracket was also performed in South Carolina.

The Inconel 718 powder used in the additive process was produced in Indiana, and the AM occurred in Florida. Therefore, the electricity mixes for these three states were used for the analysis.

The electricity-mix data for each state referenced and the U.S. average were obtained from the U.S. Energy Information Administration (EIA).[13] EIA data breaks down electricity generation by primary energy sources, which includes renewables. The electricity mixes used are shown in Table 23, and are all from 2021 or 2022.

Table 23: Electricity Mix

Utility-Scale Net Electricity Generation (share of total)	South Carolina	U.S. Average	Indiana	Florida
Petroleum-Fired	0.10 percent	0.20 percent	0.10 percent	0.20 percent
Natural Gas-Fired	27.50 percent	40.90 percent	33.30 percent	76.30 percent
Coal-Fired	14.40 percent	19.30 percent	55.60 percent	6.70 percent
Nuclear	51.40 percent	17.30 percent	0 percent	10.40 percent
Renewables	7.30 percent	21.80 percent	9.10 percent	5.30 percent

A comparison of the electricity-mix impacts can be seen for cumulative energy demand (CED) and the International Panel on Climate Change's (IPCC) global-warming potential measurement, GWP100, in Figure 30 and Figure 31 respectively, from SimaPro for 1 kWh of input. The influence of fuel source for each mix contributes to the overall impact.

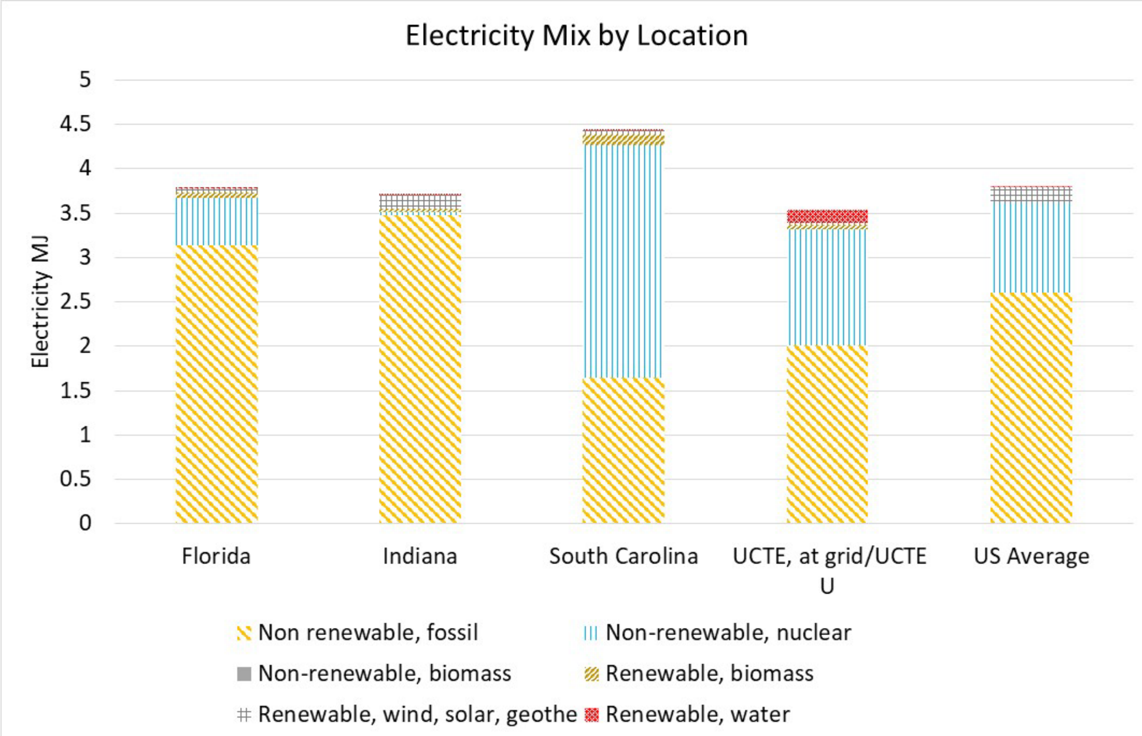


Figure 30: Electricity mix comparison by fuel source and location

Note. One kWh is equivalent to 3.6 MJ (Mega Joules) of electricity.

This data highlights not only the different energy sources, but also the difference in the efficiency of each grid. More energy is required to produce one kWh of electricity in South Carolina compared to Florida or Indiana. However, since the share of non-renewable fossil-fuel sources in South Carolina is less than that for Florida or Indiana, GWP is lower in South Carolina due to the higher percentage of nuclear power within the mix, but higher in Indiana.

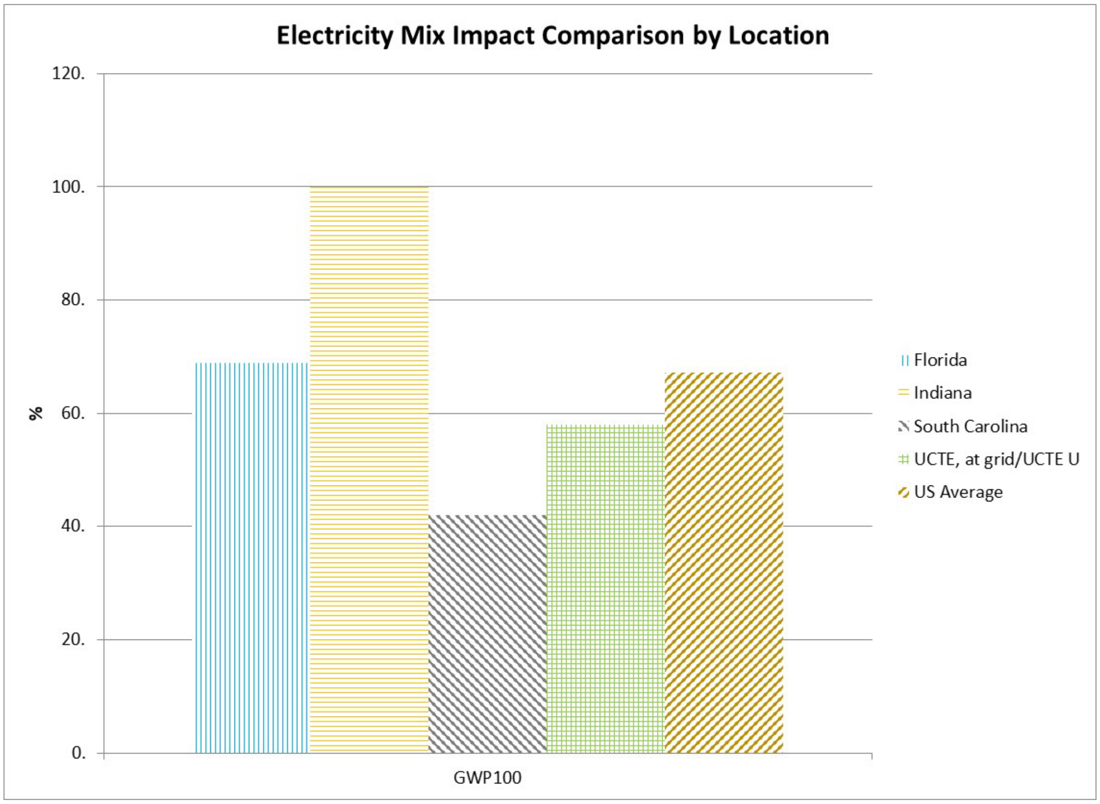


Figure 31: Electricity-mix impact comparison by location

3.5 New-Bracket Packaging

Final parts are individually packaged in single-wall cardboard boxes and wrapped in bubble wrap. The same box is assumed for each bracket design, and materials recovered for recycling at the end of life.

Material and parts packaging assumptions for this study include the following:

- Bulk materials are transported on reusable wooden pallets or in other reusable containers with multiple uses. It is assumed that the normalized mass of bulk material packaging to the mass of the transport material will be insignificant and therefore excluded from this analysis.
- Final parts are individually packaged in single wall cardboard boxes and wrapped in bubble wrap. Packaging material dimensions for each are:
    - cardboard (2.5" x 3" x 6.5") at 0.0084 kg
    - bubble wrap (4.5" x 3.5") at 0.0044 kg

Table 24: Packaging Input

SimaPro Input	Amount	Unit	Method
Corrugated board, mixed fibre, single wall, at plant/RER U	0.0084	Kg	Measured
Packaging film, LDPE, at plant/RER U	0.0044	kg	Measured

3.6 Bracket Transportation

The scope of this LCA study included the transportation pathways of materials and manufactured parts for the traditional and AM processes, illustrated in Figure 32. Locations defined in this study are derived for the baseline case study from specific locations where data was collected, material manufactured, and best estimates. Only the mass of the material required to make one LPT bracket by either manufacturing method is considered for all material transportation activities up to the part-manufacturing locations. The final part weight is used for transportation from the part manufacturer to the end user. Transportation distances are derived the defined locations and plotting a route with Google Maps. Transportation units for the study are in ton-kilometers (tkm), which is defined as moving one metric ton one kilometer.

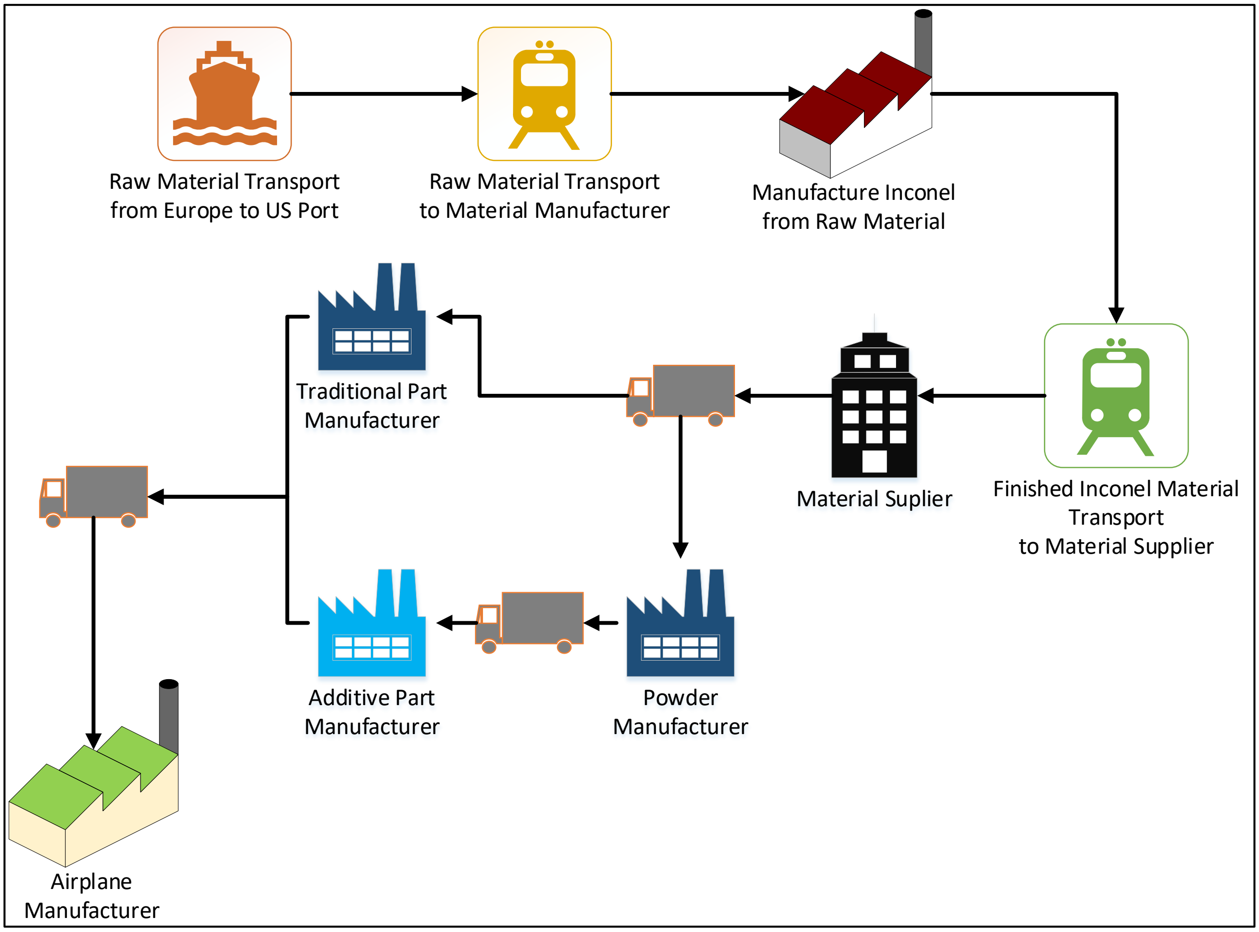


Figure 32: Transportation pathway for materials and manufactured components

The transportation pathway for Inconel 718 starts where the raw materials used to make it are first extracted. This study assumed that all of the raw materials are mined in European locations and shipped from a European port by cargo ship to the United States; more specifically from Hamburg, Germany, to a New York City port.

Once in New York City, the raw materials are transported by rail to the Inconel manufacturer in Richburg, South Carolina. At this point, the Inconel 718 alloy is created to specification and then shipped by rail in bulk bar form to a specialty-material supplier in Streamwood, Illinois. The bar material is sized in Streamwood to order and then shipped to the traditional LPT bracket manufacturer by long-haul truck service to Greenville, South Carolina.

For the AM life cycle, this study assumed that the Inconel 718 alloy for powder production is also sourced from the same specialty-material location and shipped by long-haul truck to Indianapolis, Indiana, where the powder is manufactured. The powder material is then sent to the additive LPT bracket manufacturer located in Hollywood, Florida, by long-haul truck.

The final manufactured LPT brackets in either process flow are ultimately trucked from their respective locations to a Boeing manufacturing facility located in Seattle, Washington. Transportation details are shown in Table 25 and Table 26.

Table 25: Transportation Pathways for Traditional Manufacturing Material and LPT Bracket

TRADITIONAL MANUFACTURING TRANSPORT PATHWAY						
DESCRIPTION	**START**	**END**	**DISTANCE (KM)**	**MASS: ONE BRACKET INPUT MATERIAL TRADITIONAL (METRIC TON)**	**TRANSPORT TYPE**	**TRANSPORT (TKM)**
RAW MATERIAL TO NYC PORT FROM EUROPE	Europe Hamburg Germany	NYC Harbor	7769	0.001373	Cargo Ship	10.67
RAW MATERIAL TO METAL PROCESSING FACILITY CITY TRAIN YARD	NYC	Richburg, SC 29729	1046	0.001373	Rail	1.44
ALLOY LOCATION TO BARSTOCK SUPPLIER LOCATION	ATI Specialty Materials 4374 Lancaster Highway Richburg, SC 29729	Rolled Alloys Streamwood IL 60107	1324	0.001373	Rail	1.82
BAR STOCK TO MACHINE SHOP	Rolled Alloys Streamwood IL 60107	Greenville, SC 29615	1209	0.001373	Long Haul Truck	1.66
FINISHED PART TO BOEING	Greenville, SC 29615	Boeing Seattle, WA 98108	4418	0.0001216	Long Haul Truck	0.537

Table 26: Transportation Pathways for AM Material and LPT Bracket

ADDITIVE MANUFACTURING TRANSPORT PATHWAY						
DESCRIPTION	**START**	**END**	**DISTANCE (KM)**	**MASS: ONE BRACKET INPUT MATERIAL ADDITIVE (METRIC TON)**	**TRANSPORT TYPE**	**TRANSPORT (TKM)**
RAW MATERIAL TO NYC PORT FROM EUROPE	Europe Hamburg Germany	NYC Harbor	7769	0.001358	Cargo Ship	10.55
RAW MATERIAL TO METAL PROCESSING FACILITY CITY TRAIN YARD	NYC	Richburg, SC 29729	1046	0.001358	Cargo Ship	1.42
ALLOY LOCATION TO BARSTOCK SUPPLIER LOCATION	Richburg, SC 29730	Rolled Alloys Streamwood IL 60108	1324	0.001358	Rail	1.80
SUPPLIER LOCATION TO POWDER MANUFACTUERR	Rolled Alloys Streamwood IL 60107	GLOBAL POWDER AND SLURRY MANUFACTURING Indianapolis, IN 46222 U.S.A	338	0.001358	Long Haul Truck	0.46
POWDER TO SINTAVIA	GLOBAL POWDER AND SLURRY MANUFACTURING Indianapolis, IN 46222 U.S.A	Hollywood, FL 33312	1852	0.001358	Long Haul Truck	2.52

3.7 Bracket Use Phase

The use of both the traditional and AM brackets are assumed to be the same: 125,000 flight hr of life once installed on an airplane with no required maintenance.

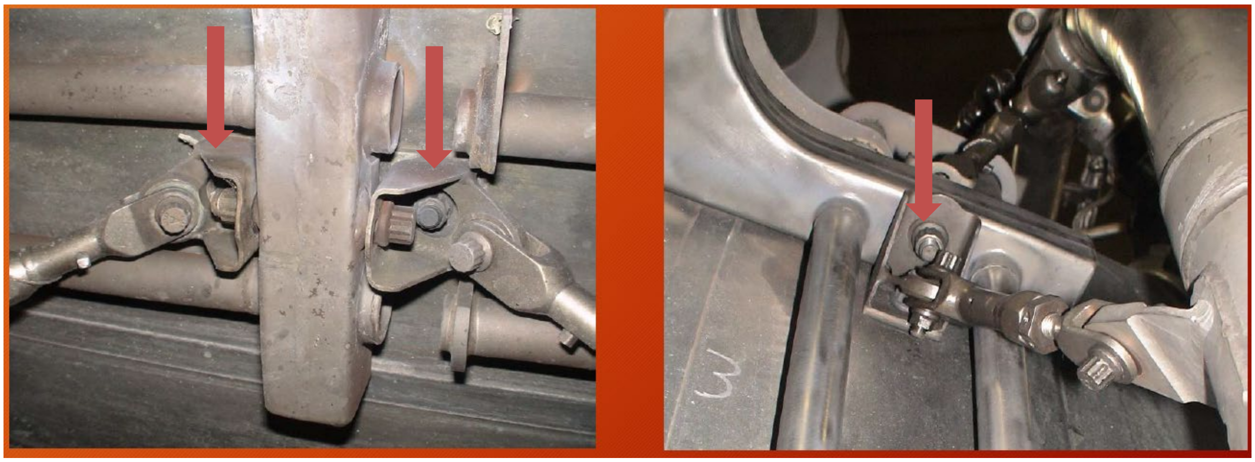


Figure 33: Installed LPT bracket

Impacts due to installation of the LPT bracket were not considered. It is assumed that both the traditional and AM brackets require the same effort to install. Primary data was not collected for this process. The LPT bracket itself does not generate any emissions or use any materials or energy during this phase of the life cycle. It is also assumed that the functionality of both brackets will be the same and receive the same routine maintenance and repair or replacement throughout this lifecycle stage; therefore, maintenance is not considered.

3.8 End-of-Life (EOL) Management

The EOL phase of the brackets is assumed to begin when the aircraft is decommissioned. Inconel 718 material is expensive and highly recoverable, and it is assumed that each bracket will be fully recycled at end of life. Recycling impacts will be allocated to the following life cycle.

3.9 Airplane-Fuel Use

An airplane's use of fuel is a major source of the flight's contribution of greenhouse gases. Since this study is comparing the weight difference between the two LPT brackets, the primary interest is in fuel use during flight. Fuel-economy data for Boeing 767 is taken from the 2019 EMEP/EEA air pollutant emissions calculator.[14] This calculator uses fuel consumption models that are based on actual flight data collected through aviation operations in Europe.

Flight regimes are defined by the International Civil Aviation Organization (ICAO). Table 27 shows fuel-burn results for the landing and take-off (LTO) and climb, cruise, and descent (CCD) stages for a travel distance representative of flights between Boston and London.[15]

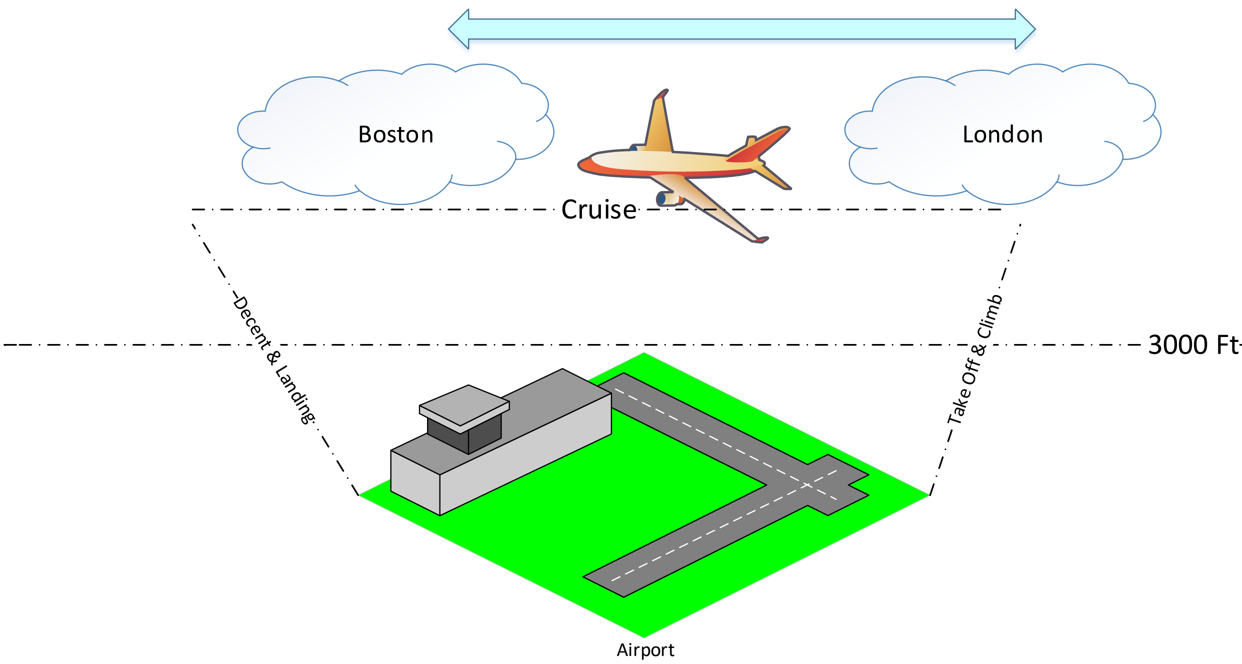


Figure 34: Depiction of London-to-Boston flight used to model aircraft fuel consumption

The adoption of lighter AM components in an aircraft will reduce its weight and, therefore, the amount of fuel used while operating the aircraft. The life cycle energy savings and GHG emissions reduction associated with these fuel savings are based on estimates of well-to-wake energy use and carbon-equivalent emissions for jet fuel used.[16]

3.9.1 B767 300ER Fuel-Consumption Analysis

To determine the fuel economy of a B767 aircraft and any potential savings due to weight reduction, a review of available data for this aircraft was conducted. For this study, the B767-300ER variant was selected as most representative of the current B767 fleet; therefore, all analysis is based on it. The goal was to define a flight profile and a lifetime operation model for the B767-300ER in order to determine the aircraft's total fuel consumption and environmental impacts. This scenario was used to reasonably predict how incremental lightweighting of the aircraft's parts would affect its performance. Analysis assumptions are defined below for representative flight characteristics.

Aircraft and Operation Assumptions

- Aircraft type: Boeing 767-300ER
- Flight itinerary: Boston to London (UAL 24) and London to Boston (UAL 25)

- Distance (one-way): 5,254 km [2,837 nautical miles (nmi)]
- Travel time from Boston to London: 6 hr 38 min
- Travel time from London to Boston: 7 hr 30 min
- Average speed: 746 km/hr

Table 27: EMEP/EEA Air-Pollutant-Emissions Calculator and Fuel-Consumption Model

	Stage Length Nautical Miles (NM)	Most frequently observed cruise-flight level (feet)	Duration (hh:mm:ss)	Fuel burn (kg)
Default LTO[a] (1) cycle	ICAO default	NA	0:32:54	1,729.93
CCD[b] (2)	**2,837**	40,000	6:16:13	28,412.77
TOTAL LTO + CCD	**2,837**	**NA**	**6:49:07**	**30,142.70**

Note. [a]NM = [Nautical Mile]; [b]CCD = Climb, cruise, and descent, refers to all activities that take place above 3,000 feet (914.4 m). No upper limit of height is given. CCD includes the climb from the end of the climb-out phase up to the cruise altitude, the cruise, and the descent from the cruise altitude to the start of the arrival phase; [c]LTO = Landing and take-off, includes take-off and climb-out, as well as approach and landing. Adapted from European Environment Agency, "EMEP/EEA air pollutant emission inventory guidebook 2019, 1.A.3.a, 1.A.5.b Aviation," by M. Winther and K. Rypdal. Copyright 2019 by the European Environment Agency.

Results of the EMEP/EEA calculator show that the overall fuel-consumption efficiency is 5.74 kg/km and the cruise efficiency (using just CCD) is 5.41 kg/km.

Boeing provides performance and fuel-consumption data for the 767 family of aircraft with different engine and seating configurations.[17] Data for the 767-300ER (extended-range variant) are provided below for a 3,000-nautical-mile (nm / 5556 km) flight and shown in Table 28. The fuel consumption (kg/km) closely matches the cruise (CCD) data from the EMEP/EEA model above.

Table 28: 767-300ER Specifications[17]

	Engines	Seating	Passengers	Fuel burn(kg)/seat (3000nm)	distance (km)	Fuel (kg)/flight	Fuel cons. (kg/km)
767-300ER	GE CF6-80C2B6F	3 class	218	137.3	5556	29931.4	5.39
767-300ER	PW4056	3 class	218	137.7	5556	30018.6	5.40
767-300ER	GE CF6-80C2B6F	2 class	269	113.9	5556	30639.1	5.51
767-300ER	PW4056	2 class	269	114	5556	30666	5.52

The design life of a Boeing 767 is 60,000 pressurization cycles or 150,000 flight hr, according to the company's quarterly publication, *Aeromagazine* (Quarter 4, 2012).[18] A recent publication on long-life aircraft shared data from Delta and United Airlines for the Boeing 767 indicating that the aircraft achieves, on average, 137,377 and 123,126 flight hr, respectively.[19] For the purposes of this study, an aircraft lifecycle of 125,000 flight hr was used. At an average speed of 746 km/hr (based on Boston to London and return travel times for a round-trip flight) the lifetime flight distance is 93.3 million km. Using the EMEP/EEA fuel economy data (5.74 kg/km including LTO phase), a baseline life cycle fuel consumption of 5.36e8 kg of jet fuel is suggested. A further sensitivity analysis will investigate the impacts for a select range of operational hours at 100,000 and 150,000 flight hr.

In regard to fuel economy due to weight reduction, a U.S. Federal Aviation Administration (FAA) study on economic drivers in aviation provides details on incremental fuel consumption due to weight effects for the Boeing 767.[20] This study is based on detailed fuel-consumption models and includes both LTO and CCD flight phases. (See Table 29.)

Table 29: Effects of Weight on Fuel Consumption for a Boeing 767 Aircraft[20]

Service Type	Aircraft Type	FAR Part	Stage Length (nautical miles)	Weight Penalty (pounds)	Incremental Fuel Burn per Flight (pounds)	Incremental Fuel Burn per Flight per Pound of Weight Added (gallons)	Flight Time (hours)	Incremental Fuel Burn per Flight Hour per Pound of Weight Added (gallons)
Passenger/ All-Cargo	B767-300	25	2,200	500	85	0.025	5.3	0.005
			5,000	500	203	0.061	11.3	0.005

Table 27 suggests that the incremental fuel burn for a 2,200-nmi flight is 4.17e-5 kg/km per kg incremental weight, for a 5000 nautical mile flight this value is 4.38e-5 kg/km per kg weight. The 2,200-nmi flight is closest to the Boston-London transatlantic flight distance, and so was used as a reliable input for this study. It also provides a conservative (lower-end benefit) value.

The fly weight of the original machined LPT bracket is 0.122 kg, while the fly weight of the AM bracket is 0.059 kg; this represents a weight savings of 0.063 kg per bracket. There are 12 brackets per Boeing 767 engine, and two engines per plane, for a total weight savings of 1.51 kg per aircraft. The operating empty weight of the aircraft varies from 90,300–92,480 kg (depending on seating and engine configuration). The bracket savings amounts to a 0.00163–0.00167-percent weight savings.

3.10 Assessment Assumptions

While much of the data was provided by AMGTA or from literature, some assumptions were required to complete the assessment.

Table 30: LCA Assumptions and Justification

Assumption ID	Assumption Description	Justification
1	Manufacturing overhead energy for both manufacturing methods considered similar—not included	Variation in manufacturing locations and manufacturer size limits the ability to determine overhead energy impacts.
2	Consumables excluded	Consumable materials not already accounted for in an Ecoinvent unit process were excluded as they would fall below the cut-off criteria of 1 percent.
3	Scrap material and EOL disposition	It is assumed that Inconel alloy is highly recoverable and will be recycled. Any non-recovered powder will go to a municipal solid waste (MSW) facility or landfill.
4	Packaging	Same packaging will be used for the traditional and additive bracket since they will be the same size

3.11 Secondary Data: LCA Databases

All material and process data provided by AMGTA were mapped to equivalent representative materials and processes included in the Ecoinvent 3.8 database compiled in 2016 with the latest revision in December 2021. Materials or processes not defined in the database are represented with material or process models that most closely reflect the original from other peer-reviewed literature sources. SimaPro 9.2 LCA software was used to translate the life cycle inventory data into environmental impacts.

Ecoinvent 3.8 data is used to provide secondary data in SimaPro. Ecoinvent data is compiled from peer reviewed life cycle assessments and peer reviewed data sets.[21] Most Ecoinvent data is collected in

Switzerland and Europe and represents the industry average in these countries. Select data points, such as the average energy mix, have been collected for the United States and are included in the database. Ecoinvent data is one of the most complete datasets of all life cycle databases commercially available. It is assumed that operations in Europe and the United States are world-class, with similar energy-usage profiles and production wastes and emissions. It is assumed that Ecoinvent data is representative of U.S. operations. U.S. data was used where available in the Ecoinvent database.

3.12 Data Quality

This section outlines the data quality requirements, as specified by ISO 14044 section 4.2.3.6.2.

3.12.1 Consistency, Precision, and Completeness

Consistency considers how uniformly the study methodology is applied to the various components of the analysis. The methodologies, modeling parameters, and assumptions outlined above were applied to all configurations and scenarios equivalently.

Precision is a measure of the variability of data values within each data category. Because only one data set was available for each configuration, there is no alternate point of reference to which precision can be measured. In order to assess variability, a literature review was performed for machining of Inconel material to better understand the energy requirements for this process. Also assessed were the variability of electricity mix based on manufacturing location and material input, which is discussed further in the sensitivity and uncertainty analysis.

Completeness measures the portion of used data collected through primary means for each category in a unit process. Actual material and process data was collected for the additively manufactured LPT bracket. Locations for material and parts manufacturing are known and used for determining transport distances between locations.

Assumptions were made for the source or the primary materials used to produce the Inconel material and how it was transported due to lack of primary data. Also assumed was the final destination of the finished parts to the aircraft manufacturer, based on known location for Boeing manufacturing facilities.

3.12.2 Representativeness

Representativeness is an assessment of how the dataset used in the LCA model reflects the true system. Material and manufacturing data were provided by AMGTA for both the traditional manufacturing and AM processes. The data is derived directly from real-world systems used.

3.12.3 Temporal, Geographic, and Technological Representativeness

Temporal representativeness describes the age of data and the minimum length of time for which data was collected. All primary data was collected between September 2021 and March 2022, and represents current manufacturing practices.

Geographic representativeness describes the geographic area from which unit process data is collected for the study. The impacts of manufacturing energy use are based on expected impacts from location specific electrical generation grid mixes for the different manufacturing regions.

Technological representativeness describes how well the dataset used to develop the LCA model represents the true technological characteristics of the system. Actual materials were identified through material supplier's specification sheets, test reports and literature search. All operations were performed on typical equipment used in the manufacturing processes of the LPT bracket. It is important to note that the traditional manufacturing run could be considered a prototyping process and not fully optimized for a production run.

3.12.4 Reproducibility

LCA modeling was performed and documented such that this assessment can be reproduced by another practitioner. This report contains all life cycle inventory data and all assumptions used to calculate the environmental impact of each configuration.

3.12.5 Source of Data

The data source for all data is provided in Appendices A ("Material Data Sources"), B ("Additive Manufacturing Primary Data") and C ("Traditional Manufacturing Primary Data"). Primary manufacturing data was collected directly at both manufacturing sites by their respective staff with direction and guidance from GIS. This data includes energy consumption along with material inputs and outputs. Material data was obtained from material-supplier specification sheets and test reports.

3.12.6 Data Uncertainty

Variability exists in process inputs and outputs. It is built into Ecoinvent unit processes as a distribution around the data sources where available. The goal of uncertainty analysis is to understand how variation in an assessment's data and assumptions may affect the LCA results. A pedigree matrix was used to determine the uncertainty distribution for materials, processes and transport used in this study shown in Table 31.

SimaPro was used to perform uncertainty analyses of the scenarios using the Monte Carlo method. Each scenario was run 1,000 times at 95 percent confidence. The uncertainty comparison was made between the traditionally machined and AM LPT brackets using the CED and GWP100 method.

Table 31: Uncertainty Values Derived from Pedigree Matrix

Process/Material	Mean Value	Max	Min	Units	Distribution	SD2 or 2SD
!!2aa_Inconel 718 Heat Treat Process AM	2	NA	NA	kwh	Lognormal	1.05
!!2aa_Inconel 718 Heat Treat Process Traditional	2.3	NA	NA	kwh	Lognormal	1.05
!!3_Inconel 718 Powder Production Process	0.277	0.4	0.146	kwh	Uniform	NA
!!1_Traditional LPT Bracket Machining Process	4.5	NA	NA	kwh	Lognormal	1.58
!!1_Traditional LPT Bracket Machining Process	4.8	NA	NA	kwh	Lognormal	1.59
!!1_Traditional LPT Bracket Machining Process	44.757	72.398	30.275	kwh	Uniform	NA
!!2_Wire EDM Traditional	8.8	NA	NA	kwh	Lognormal	1.21
!!2_Wire EDM Traditional	162	NA	NA	cuft	Lognormal	1.22
!!3_Media Blast	0.227	NA	NA	kg	Lognormal	1.22
!!3_Media Blast	0.046	NA	NA	kwh	Lognormal	1.22
!!5_FPI Inspection	0.2	NA	NA	kwh	Lognormal	1.65
!!6_CMM Inspection Traditional	0.1786	NA	NA	kwh	Lognormal	1.22
!!8_Transport to Boeing Manufacturing	0.53718	NA	NA	tkm	Lognormal	1.05
!!1_AM Process EOS 400 Printer	30.81	62.1524	20.0819	kwh	Uniform	NA
!!3_Stess Relief (Heat Treat) HVF-401B Furnace	0.5283	NA	NA	kwh	Lognormal	1.21
!!3_Stess Relief (Heat Treat) HVF-401B Furnace	2.536	NA	NA	kg	Lognormal	1.21
!!4_Wire EDM	11.732	NA	NA	kwh	Lognormal	1.21
!!5_Debur and Finish Additive	0.7583	NA	NA	kg	Lognormal	1.05
!!5_Debur and Finish Additive	0.075	NA	NA	kwh	Lognormal	1.24
!!6_CMM Inspection AM	0.1786	NA	NA	kwh	Lognormal	1.22
!!9_Transport of AM Part to Boeing	0.3135	NA	NA	tkm	Lognormal	1.05

4 Life Cycle Impact Assessment (LCIA)

LCIA is the phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. The purpose of this impact assessment is thus to interpret the life cycle GHG emissions and resource-consumption inventory for both the traditionally manufactured and AM brackets.

4.1 LCIA Methods

Impact assessment calculations were performed using SimaPro version 9.2.0.2 LCA software. This software has multiple native impact assessment methods. The goal of this study was to assess the energy consumption and global warming potential associated with the life cycle of both additively manufactured and traditionally manufactured brackets. To accomplish this, GIS selected to use two well established methods: ReCiPe and CED. We also selected the IPCC 2021 GWP100 as a metric, because it is believed to better reflect current conditions than the version used in ReCiPe. Furthermore, ReCiPe also includes factors that pertain to the effects of fuel production and combustion, making it a more comprehensive method for evaluating the life cycle of the brackets. The methods chosen for this analysis are detailed below.

4.1.1 ReCiPe v1.1 (2016)

One of the main impact assessment methods used in this analysis is the internationally recognized ReCiPe Midpoint H v1.11 (2016) LCA methodology. It was selected for its comprehensive spectrum of impact categories. The 18 impact categories addressed in ReCiPe are shown in Table 32.[22]

Table 32: ReCiPe impact categories

Impact category	Characterization factor	abbreviation	Unit
climate change	global warming potential	GWP	kg (CO_2 to air)
ozone depletion	ozone depletion potential	ODP	kg (CFC-11 to air)
terrestrial acidification	terrestrial acidification potential	TAP	kg (SO_2 to air)
freshwater eutrophication	freshwater eutrophication potential	FEP	kg (P to freshwater)
marine eutrophication	marine eutrophication potential	MEP	kg (N to freshwater)
human toxicity	human toxicity potential	HTP	kg (14DCB to urban air)
photochemical oxidant formation	photochemical oxidant formation potential	POFP	kg (NMVOC to air)
particulate matter formation	particulate matter formation potential	PMFP	kg (PM_{10} to air)
terrestrial ecotoxicity	terrestrial ecotoxicity potential	TETP	kg (14DCB to industrial soil)
freshwater ecotoxicity	freshwater ecotoxicity potential	FETP	kg (14DCB to freshwater)
marine ecotoxicity	marine ecotoxicity potential	METP	kg (14-DCB to marine water)
ionizing radiation	ionizing radiation potential	IRP	kg (U^{235} to air)
agricultural land occupation	agricultural land occupation potential	ALOP	$m^2 \times yr$ (agricultural land)
urban land occupation	urban land occupation potential	ULOP	$m^2 \times yr$ (urban land)
natural land transformation	natural land transformation potential	NLTP	m^2 (natural land)
water depletion	water depletion potential	WDP	m^3 (water)
mineral resource depletion	mineral depletion potential	MDP	kg (Fe)
fossil resource depletion	fossil depletion potential	FDP	kg (oil)

4.1.2 Cumulative Energy Demand (CED) v1.09

This analysis also used the CED v1.11 impact-assessment method, which is accepted internationally.[23] The CED of a product represents the total direct and indirect energy use, and fuels used for feedstock, throughout the product life cycle, measured in mega joules (MJ), and is widely used as a screening indicator for environmental impacts.[23]

Table 33: Cumulative Energy Demand (CED) in Ecoinvent: Category and sub category[23]

	subcategory	includes
non-renewable resources	fossil	hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat
	nuclear	uranium
	primary forest	wood and biomass from primary forests
renewable resources	biomass	wood, food products, biomass from agriculture, e.g. straw
	wind,	wind energy
	solar	solar energy (used for heat & electricity),
	geothermal	geothermal energy (shallow: 100-300m)
	water	run-of-river hydro power, reservoir hydro power

The CED method was also chosen for this analysis to provide additional detail to specific processes and materials that may have significant embodied energy requirements.

4.1.3 IPCC 2021 GWP100

The IPCC 2021 GWP100 is the successor of the IPCC 2013 method, which was developed by the IPCC. It utilizes GWP100, which is a measure of a gas's potency as a contributor to global warming over one hundred years. The GWP100 factors are recommended as default by the U.N. Environment Programme's 2017 global life cycle impact assessment method (UNEP-GLAM), and the GWP20 and GTP100 factors for sensitivity analysis.[24]

Importantly, the version of GWP100 method chosen for this study does not take into account the carbon dioxide absorbed by plants and trees and the carbon-dioxide emissions from living organisms, because these happen quickly and do not have a net effect on the environment. Additionally, the way methane emissions from living organisms are calculated has been corrected to account for the carbon dioxide absorbed by plants and trees.

The results can be calculated cumulatively as GWP100 or per category, as shown in the following:

- GWP100 - fossil
- GWP100 - biogenic
- GWP100 - land transformation

The GWP100 method is based on the *AR6 Climate Change 2021: The Physical Science Basis*, an IPCC report.

4.2 Ecoinvent Database

The Ecoinvent 3.8 database was used for this analysis. Ecoinvent data is maintained by the Ecoinvent Research Centre. Created in 1997, the Ecoinvent Research Centre (originally called the Swiss Centre for Life Cycle Inventories) is a Competence Centre of the Swiss Federal Institute of Technology Zürich (ETH Zurich) and Lausanne (EPF Lausanne), the Paul Scherrer Institute (PSI), the Swiss Federal Laboratories for Materials Testing and Research (EMPA), and the Swiss Federal Research Station Agroscope Reckenholz-Tänikon (ART).[25]

The following is adapted from the Code of Practice, Data v3.8 (2016), published by the Swiss Centre for Life Cycle Inventories at the Ecoinvent Centre:

> The Ecoinvent data comprise life cycle inventory data covering energy (including oil, natural gas, hard coal, lignite, nuclear energy, hydro power, photovoltaics, solar heat, wind power, electricity mixes, and bioenergy), transport, building materials, wood (European and tropical wood), renewable fibres, metals (including precious metals), chemicals (including detergents and petrochemical solvents), electronics, mechanical engineering (metals treatment and compressed air), paper and pulp, plastics, waste treatment, and agricultural products.
>
> The entire system consists of about 4,000 interlinked datasets. Each dataset describes a life cycle inventory on a unit-process level. The functional unit of all these unit processes is either a product or a service (whereby the product may be as large as one complete power plant manufactured for producing electricity).
>
> A brief description of the database nomenclature is provided below.
>
> - Categories and subcategories are also used to describe the elementary flows.
> - Elementary flows are identified by the flow name (e.g., “carbon dioxide, fossil”), the category and the subcategory, and the unit.
> - Categories describe the different environmental compartments air, water, soil, and resource uses.
> - Subcategories further distinguish sub-compartments within these compartments that may be relevant for the subsequent impact-assessment step.
> - The categories "air," "water," and "soil" describe the receiving compartment and are used for (direct) pollutant emissions, whereas the category "resource" is used for all kinds of resource consumption. For instance, water consumption is recorded as an input in the category/subcategory "resource/in water," and land transformation and occupation is recorded as an input in the category/subcategory "resource/land."

4.3 LCIA Limitations

As with any LCA, there are limitations on how the results should be used. LCA results should not be considered the only source of environmental information on a product or process. The goal of this study was to compare the manufacture of an LPT bracket by AM and traditional manufacturing methods along with the related energy and greenhouse gas impacts. Limitations of this study can be attributed to lack of data on Inconel powder production related to energy use as waste. For this study, data from similar processes was used and assumed to be representative.

Another limitation is related to the lack of real-time energy data for the traditional manufacturing process of the Inconel bracket. Data provided for this process was not representative of the machining process but rather the machine platform power ratings and specifications. For this reason, values found in literature are used and discussed previously.

Other limitations can be attributed to the impact assessment where methods may not consider the effects of climate change, for example. Other limitations are the representativeness to current conditions such as the GWP within ReCiPe 2016 midpoint (H) compared to GWP in the IPCC 2021 GWP100.

4.4 Value Choice

Throughout this study, value choices have been made regarding the data and methods. Having only one source of primary data for the manufacture of the LPT bracket by AM and traditional methods required additional thought and research related to process energy of machining Inconel. Values were selected that were thought to be most representative of the current process, within a range, for the uncertainty analysis.

Another value choice is using specific electricity grid mixes based on manufacturing and material production locations. Some electricity grid mixes are more favorable than others; therefore, a sensitivity analysis was run comparing the U.S. average grid mix in order to eliminate the variability of grid location.

Impact methods selected are based on the goals of the study to determine the energy and greenhouse gas impacts from manufacturing and fuel use from aircraft flight for both brackets. The 2021 GWP100 Method was chosen due to the fact it is a more recent method for GWP compared to the one in ReCiPe.

5 Results

One of the study goals was to compare the life cycle environmental impacts of an AM-made bracket used for mounting commercial aircraft-engine components to those of a traditionally machined bracket. This analysis was initially completed by using two baseline case studies with primary data collected for both processes. Using this data, a contributional analysis was done to identify areas in both manufacturing processes that significantly contribute to the environmental impacts.

This study sought to make conclusions that applied more broadly than just to the baseline case studies. Therefore, sensitivity and uncertainty analyses were completed to determine the robustness of the baseline assessment results. These exercises aimed to determine if different datasets (like manufacturing location and relative grid-based energy mix) or different assumptions (like the ratio of machining energy to the amount of material removed) would lead to different conclusions than what was observed in the original case studies.

The research also evolved to take in additional considerations that would provide a more comprehensive understanding of how an AM-produced LPT bracket might contribute to sustainable aviation during its use phase. This inquiry stemmed from an understanding that weight has a significant impact on airplane fuel use. This study therefore also analyzed part weight, contrasting the environmental impacts of fuel use during aircraft operation to the life cycle impacts of manufacturing the brackets using traditional machining or AM.

5.1 Environmental Impacts of Baseline Case Studies

The environmental impact results for both case studies are reported in the following sections. The climate-change midpoint was selected for closer analysis and is also described in the following section.

5.1.1 AM-Bracket Case-Study Results

Figure 35 shows results for the ReCiPe midpoint method, which indicate that the material and processing stages for AM dominate each category. The material phase has significant impacts for water consumption and human carcinogenic toxicity, both at over 80 percent. The process stage of the AM manufacturing has significant impacts for global warming and fossil-resource scarcity.

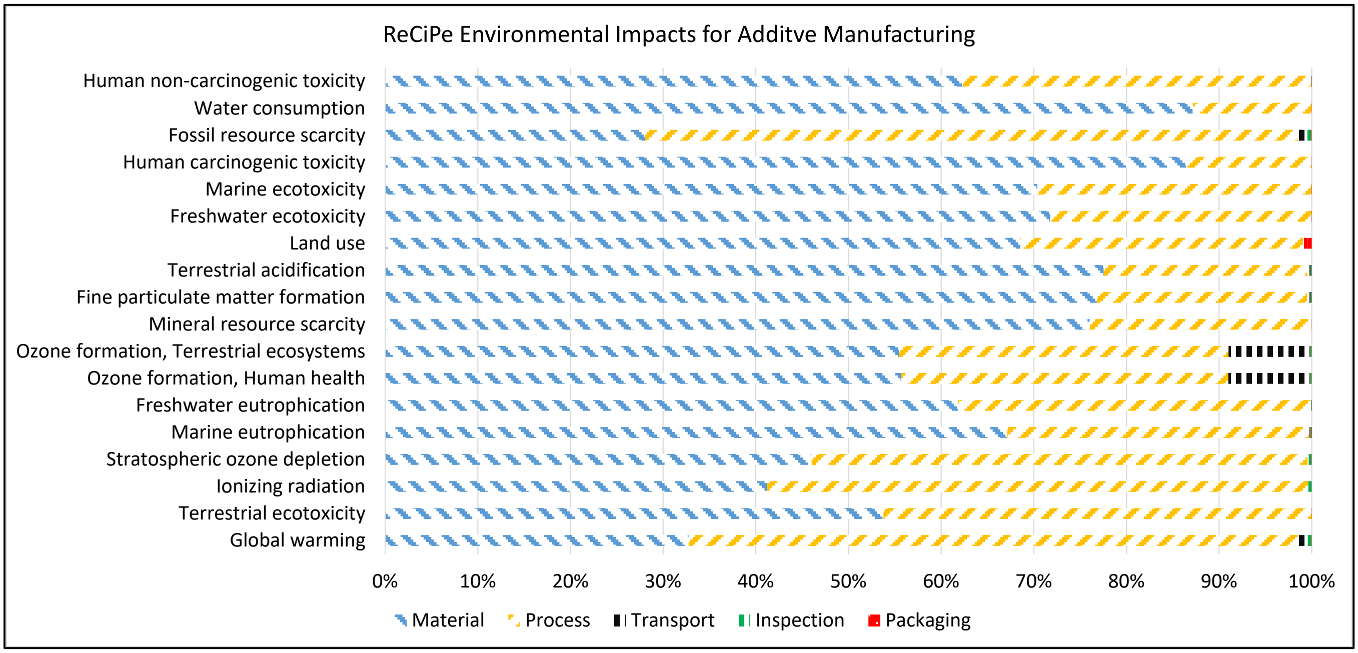


Figure 35: ReCiPe environmental impacts for AM

The values for the AM impacts can be seen in Table 34 for each impact category and process along with the total impact.

Table 34: ReCiPe Environmental Impacts for AM

		Material	Process	Transport	Inspection	Packaging	Total
kg CO2 eq	Global warming	18.7	37.5	0.6	0.22	0.02	56.98
kg 1,4-DCB	Terrestrial ecotoxicity	630.7	541.8	0.0	0.31	0.02	1172.78
kBq Co-60 eq	Ionizing radiation	6.5	9.1	0.0	0.06	0.00	15.65
kg CFC11 eq	Stratospheric ozone depletion	1.01E-05	1.17E-05	2.62E-08	6.64E-08	7.74E-09	2.19E-05
kg N eq	Marine eutrophication	1.71E-03	8.28E-04	2.80E-06	2.98E-06	2.14E-06	2.54E-03
kg P eq	Freshwater eutrophication	0.0385	0.0237	0.0000	4.25E-05	4.29E-06	0.0623
kg NOx eq	Ozone formation, Human health	0.0704	0.0447	0.0112	1.99E-04	4.22E-05	0.1265
kg NOx eq	Ozone formation, Terrestrial ecosystems	0.0706	0.0453	0.0112	2.03E-04	4.23E-05	0.1273
kg Cu eq	Mineral resource scarcity	3.6	1.1	0.00E+00	3.55E-04	3.88E-05	4.73
kg PM2.5 eq	Fine particulate matter formation	0.3	0.1	1.58E-03	4.98E-04	2.01E-05	0.43
kg SO2 eq	Terrestrial acidification	1.1	0.3	4.95E-03	1.67E-03	5.75E-05	1.40

		Material	Process	Transport	Inspection	Packaging	Total
m2a crop eq	Land use	0.5	0.2	0.00E+00	9.27E-04	6.35E-03	0.76
kg 1,4-DCB	Freshwater ecotoxicity	9.4	3.7	2.96E-03	3.52E-03	2.67E-04	13.08
kg 1,4-DCB	Marine ecotoxicity	12.8	5.4	3.99E-03	4.96E-03	3.76E-04	18.18
kg 1,4-DCB	Human carcinogenic toxicity	21.4	3.4	4.10E-04	6.12E-03	6.19E-04	24.79
kg oil eq	Fossil resource scarcity	4.9	12.3	1.78E-01	0.07	9.96E-03	17.42
m3	Water consumption	630.7	92.7	0.00E+00	0.17	3.21E-02	723.59
kg 1,4-DCB	Human non-carcinogenic toxicity	302.7	182.6	0.2	0.17	9.00E-03	485.61

The AM impacts for CED shown in Figure 36 and Figure 37 indicate that the process energy has the greatest impact.

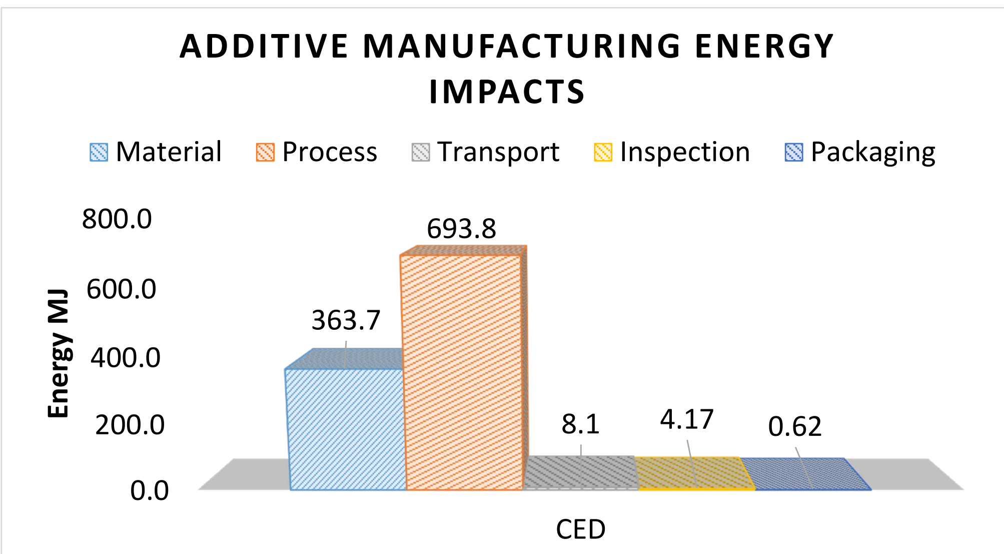


Figure 36: AM-energy impacts by category

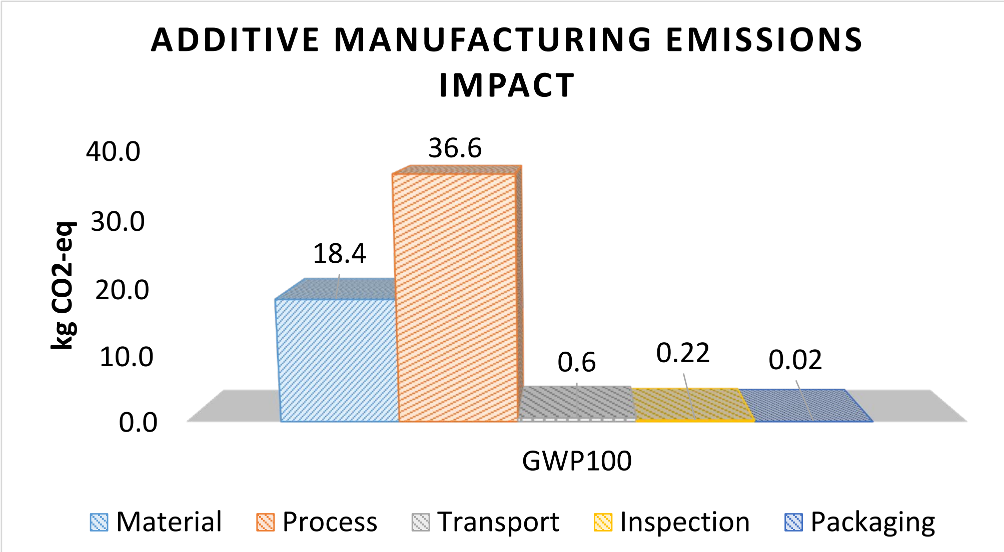


Figure 37: AM emissions impacts by category

5.1.2 Machined-Bracket Case-Study Results

Figure 38 shows results for the ReCiPe midpoint system. The data indicates that the material and processing stages for traditional manufacturing dominate each category. While the material category appears to dominate a majority of the impacts, the processing has significant impact for ionizing radiation and fossil-resource scarcity.

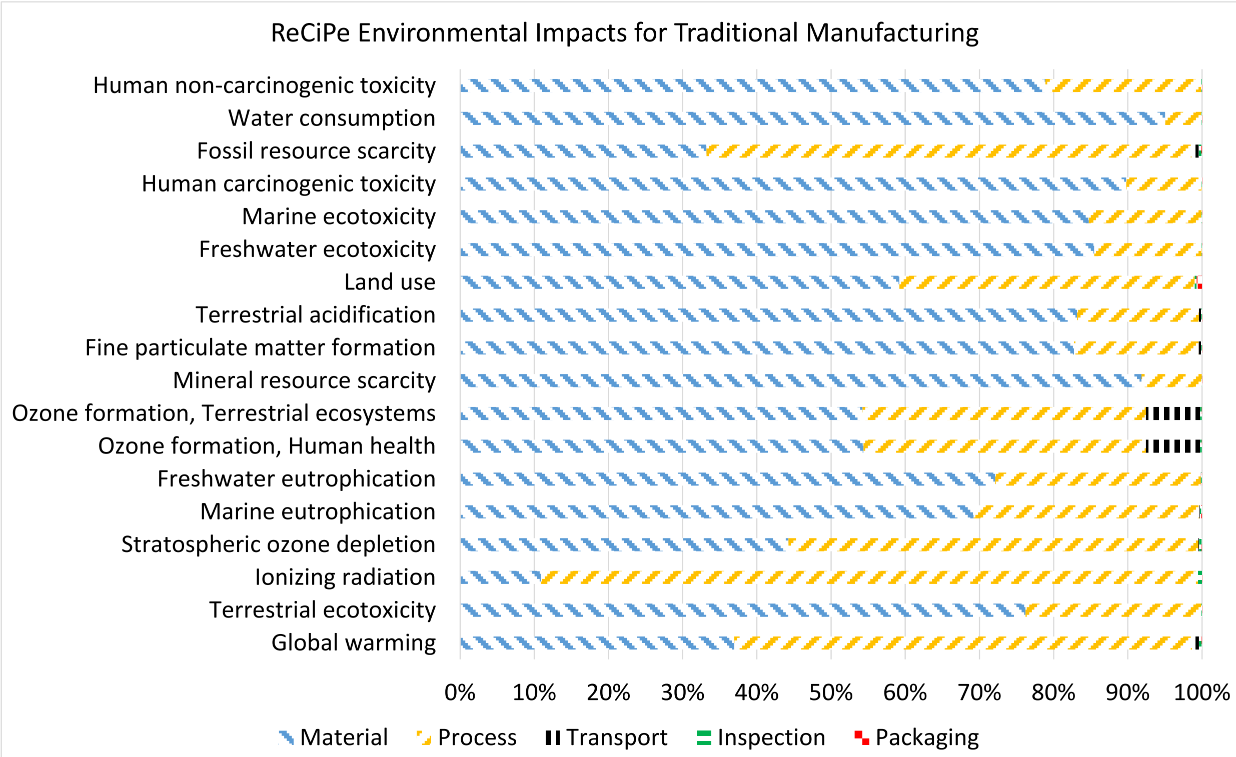


Figure 38: ReCiPe environmental impacts for traditional manufacturing

The table of values for the traditional manufacturing ReCiPe impacts can be seen in Table 35.

Table 35: ReCiPe Environmental Impacts for Traditional Manufacturing

		Material	Process	Transport	Inspection	Packaging	Total
kg CO2 eq	Global warming	18.7	31.3	0.5	0.19	0.02	50.67
kg 1,4-DCB	Terrestrial ecotoxicity	637.9	198.6	0.0	0.50	0.02	837.06
kBq Co-60 eq	Ionizing radiation	6.3	50.8	0.0	0.31	0.00	57.40
kg CFC11 eq	Stratospheric ozone depletion	0.0	0.0	0.0	0.00	0.00	0.00
kg N eq	Marine eutrophication	0.0	0.0	0.0	0.00	0.00	0.00
kg P eq	Freshwater eutrophication	0.0	0.0	0.0	0.00	0.00	0.05
kg NOx eq	Ozone formation, Human health	0.1	0.0	0.0	0.00	0.00	0.13
kg NOx eq	Ozone formation, Terrestrial ecosystems	0.1	0.1	0.0	0.00	0.00	0.13

		Material	Process	Transport	Inspection	Packaging	Total
kg Cu eq	Mineral resource scarcity	3.6	0.3	0.000000	0.00	0.00	3.97
kg PM2.5 eq	Fine particulate matter formation	0.3	0.1	0.0	0.00	0.00	0.41
kg SO2 eq	Terrestrial acidification	1.1	0.2	0.0	0.00	0.00	1.32
m2a crop eq	Land use	0.5	0.4	0.0	0.00	0.01	0.88
kg 1,4-DCB	Freshwater ecotoxicity	9.5	1.6	0.0	0.01	0.00	11.11
kg 1,4-DCB	Marine ecotoxicity	12.9	2.3	0.0	0.01	0.00	15.28
kg 1,4-DCB	Human carcinogenic toxicity	21.7	2.5	0.0	0.01	0.00	24.15
kg oil eq	Fossil resource scarcity	4.9	9.6	0.144418	0.06	0.01	14.75
m3	Water consumption	638.1	33.1	0.000000	0.21	0.03	671.38
kg 1,4-DCB	Human non-carcinogenic toxicity	306.1	81.5	0.1	0.26	0.01	388.07

Figure 39 shows the energy impacts for the traditional manufacturing cradle-to-gate phase. This indicates that the process stage contains the greatest energy impact, followed by the material stage.

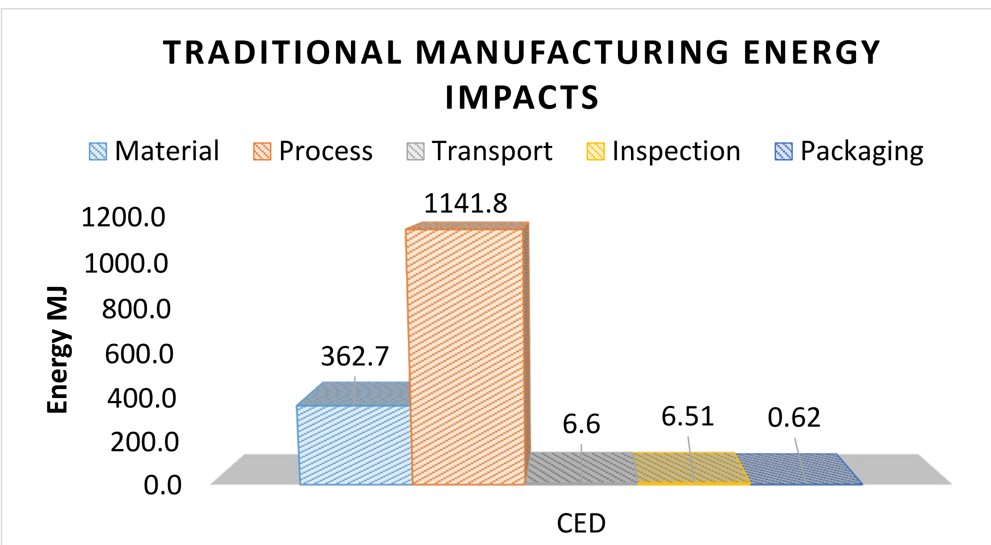


Figure 39: Traditional Manufacturing Energy Impacts by Category

For the GWP100 analysis, the traditional method shows a slight benefit over the additive one for the cradle-to-gate phases (see in Figure 40). This difference is primarily in the process phase, while the rest are almost identical.

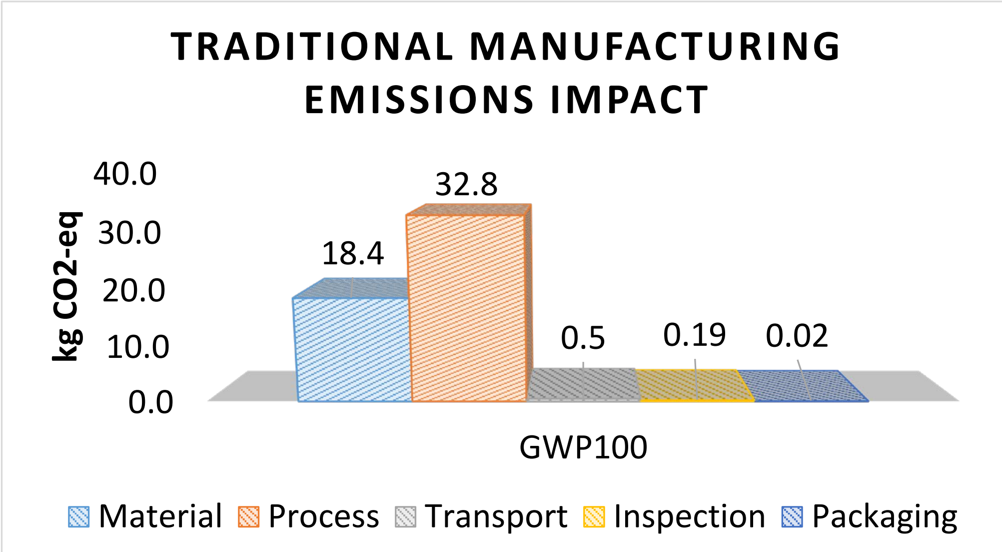


Figure 40: Traditional manufacturing emissions impacts by category

5.1.3 Comparing Case-Study Results

A normalized comparison between the two manufacturing methods (Figure 41) shows that the traditional manufacturing has a slight advantage over the additive process in thirteen of the eighteen impact categories.

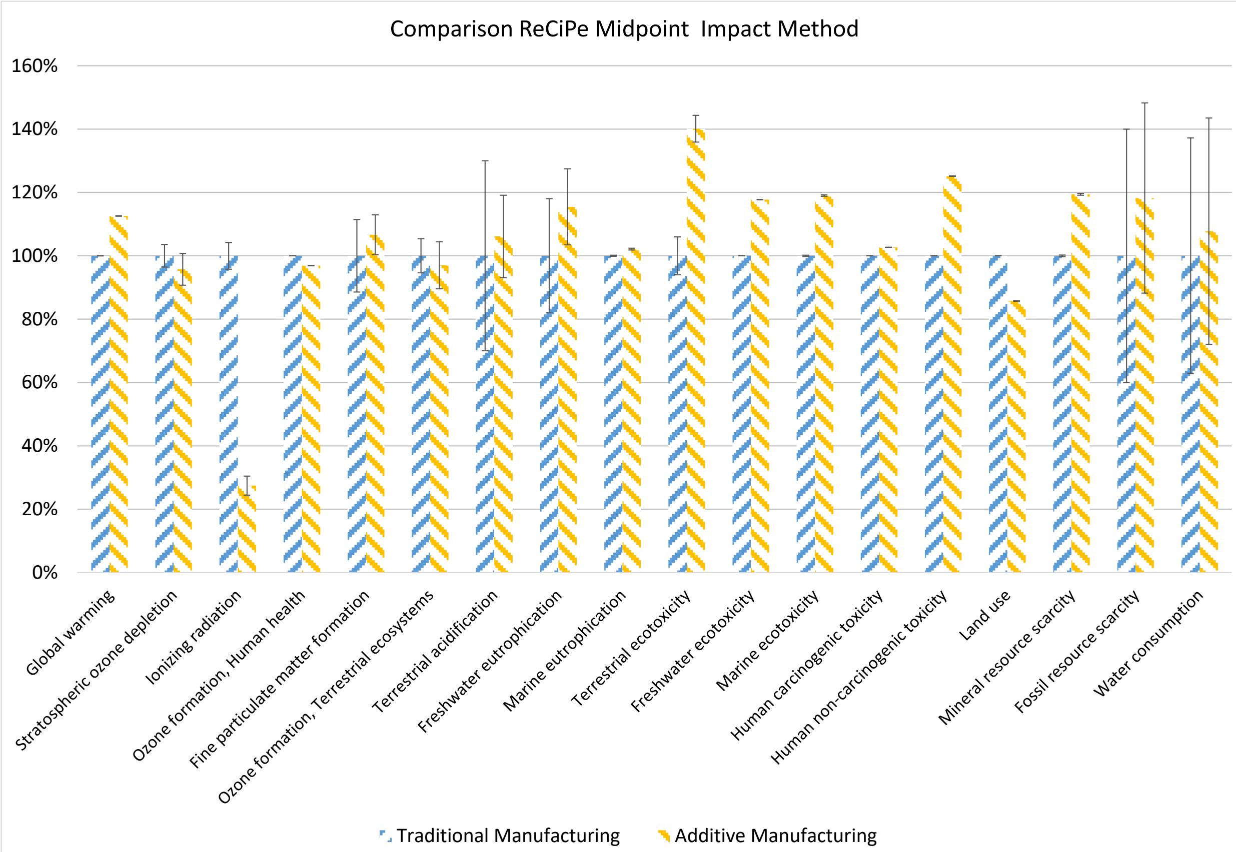


Figure 41: ReCiPe impact method comparison of traditional and AM

Figure 42 shows that an overall comparison for CED between the two manufacturing methods suggests that AM uses less energy in this particular scenario. Uncertainty analysis shows that the confidence in these results is less than 95 percent, which is discussed further in the following sections. Error bars in the graph relate to the uncertainty associated with the data.

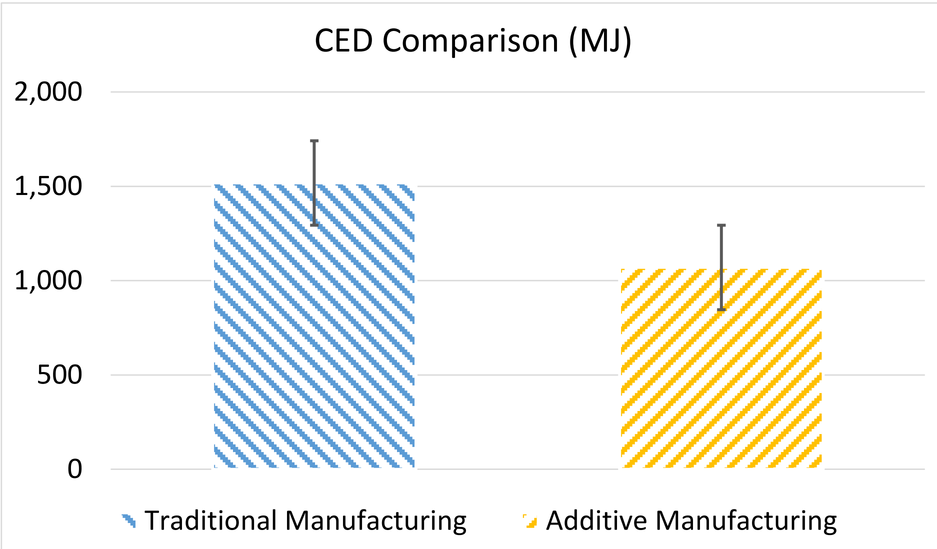


Figure 42: CED comparison between manufacturing methods

A breakdown of the life cycle categories for each method shown in Figure 43 (CED analysis) and Figure 44 (GWP100 analysis) both indicate that the manufacturing process is the most impactful phase in both instances. Otherwise, the remaining categories are nearly equivalent between the two.

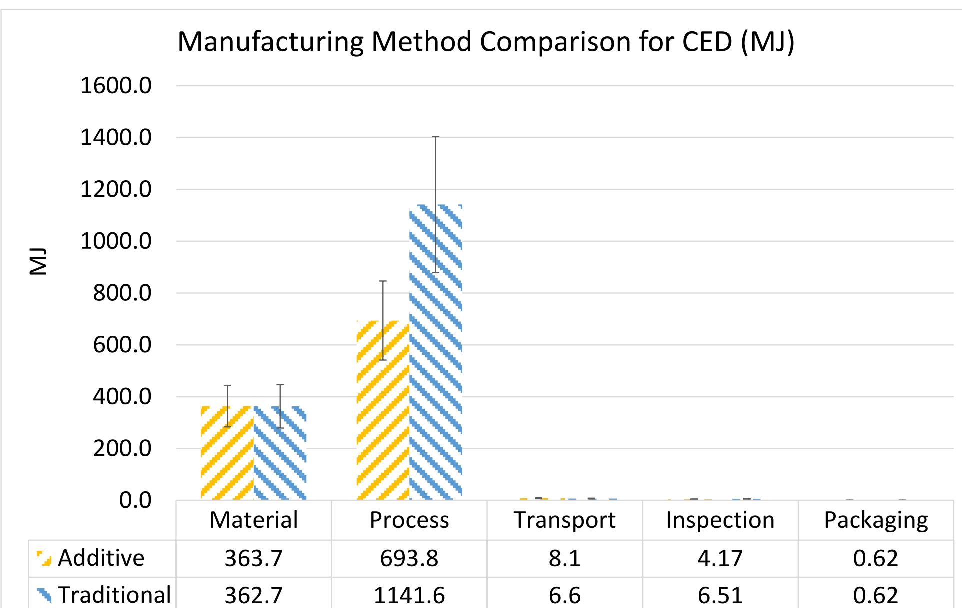
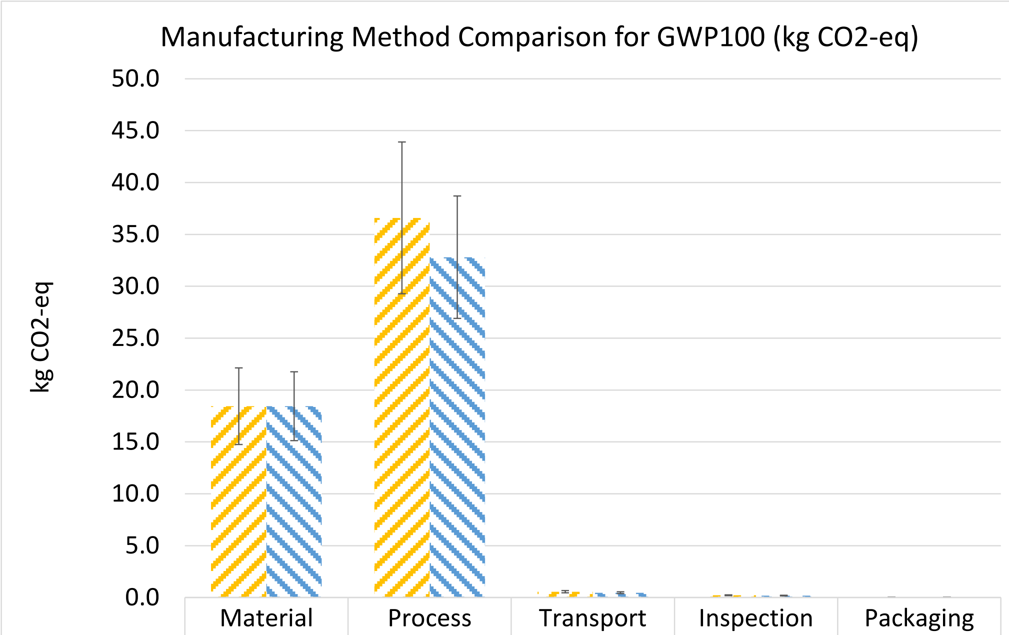


Figure 43: Comparison of cradle-to-gate life cycle categories for CED



	Material	Process	Transport	Inspection	Packaging
Additive	18.4	36.6	0.6	0.22	0.02
Traditional	18.4	32.8	0.5	0.19	0.02

Figure 44: Comparison of life cycle categories cradle-to-gate for GWP100

5.2 Broadening the Case Studies

As mentioned at the opening of this section, this study intended to support conclusions that can apply to more diverse scenarios than those defined in the baseline case studies. To this end, sensitivity and uncertainty analyses were completed to determine the robustness of the baseline assessment results and to conclude whether different datasets or assumptions would change general conclusions.

5.2.1 Sensitivity Analysis

5.2.1.1 Energy Mix Sensitivity Analysis

This report refers to the energy mix (or power-generation mix) as the group of different energy sources from which grid electricity is produced. Energy production by fuel type varies by location, where some areas favor more energy from renewable sources such as wind, solar, and hydroelectric, and others favor production from fossil fuels such as coal and petroleum products. Variation in energy production by fuel type may have a discernable impact on the environmental results. A sensitivity analysis was performed for the various energy mixes used in the base case analysis. The main analysis used energy mixes from the different manufacturing areas to build the model. This sensitivity analysis uses an average U.S. energy mix for both methods to eliminate variability of energy mix and location.

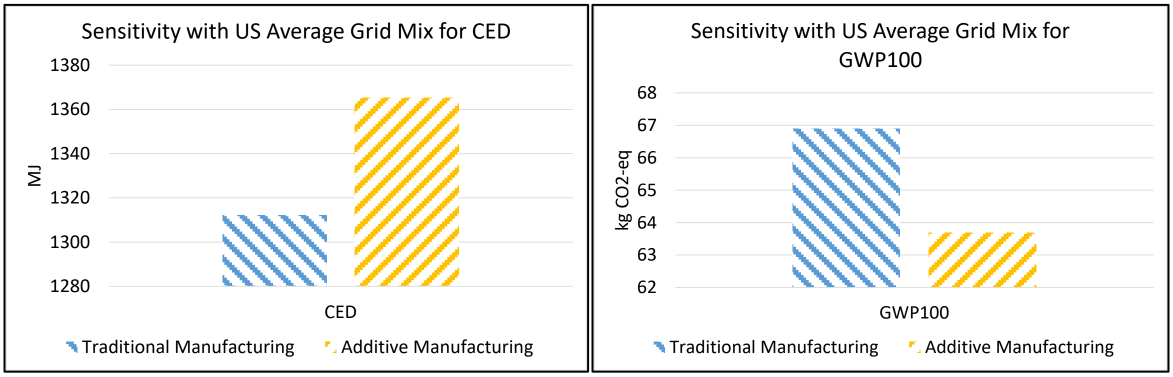


Figure 45: Sensitivity for CED (left) and GWP100 (right) using U.S. average grid mix for AM and traditional machining

Figure 46 compares impacts for individual cradle-to-gate categories for both manufacturing methods.

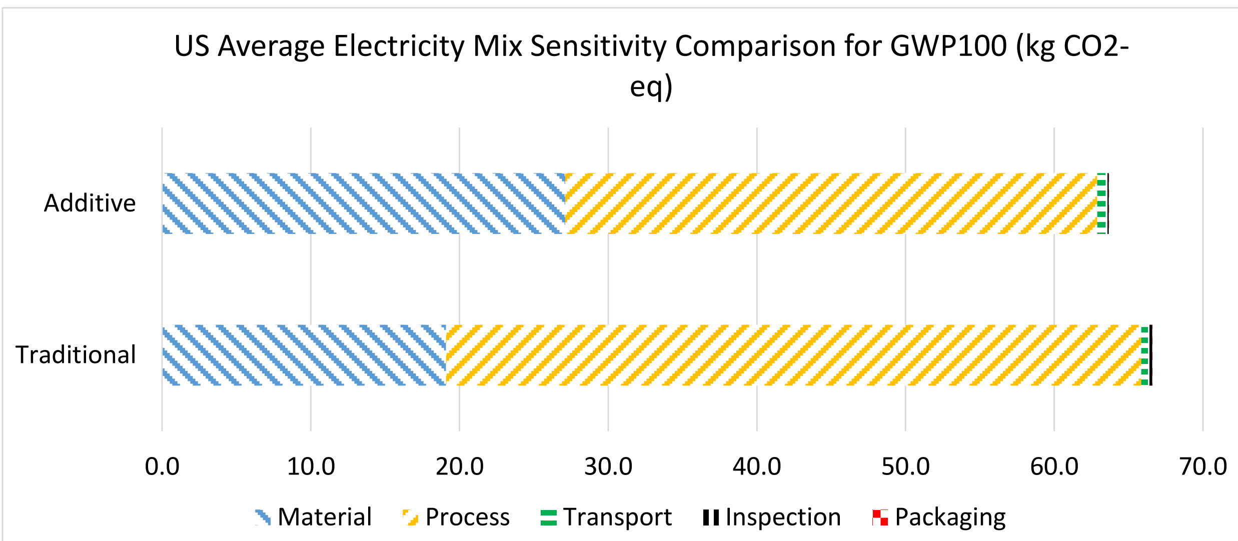


Figure 46: Energy-mix sensitivity manufacturing comparison for GWP100

Figure 47 and Figure 48 illustrate the difference in energy use and carbon emissions respective to AM and traditional manufacturing according to different energy-mix models. “Specific mix” refers to the electricity used by the actual manufacturing locations in this study. Because of the variability of energy service from one locale to another, we could not clearly determine whether either of the case studies was, in all aspects, more sustainable than the other.

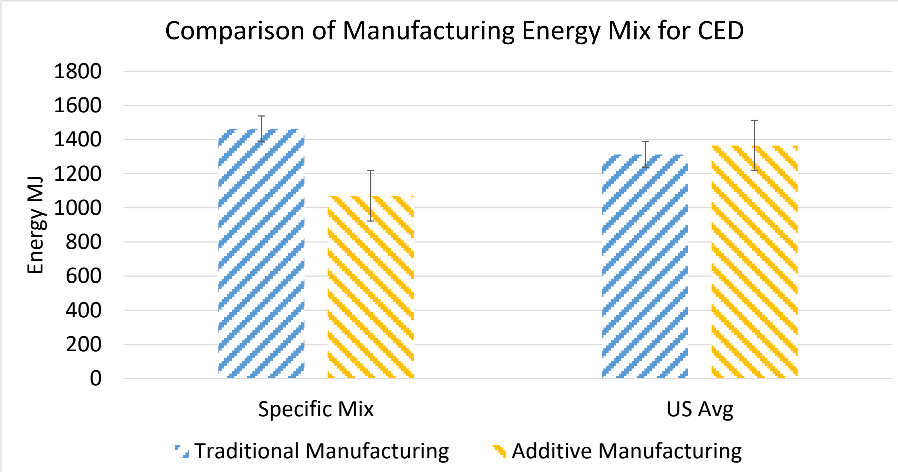


Figure 47: Energy-mix impacts on manufacturing for CED

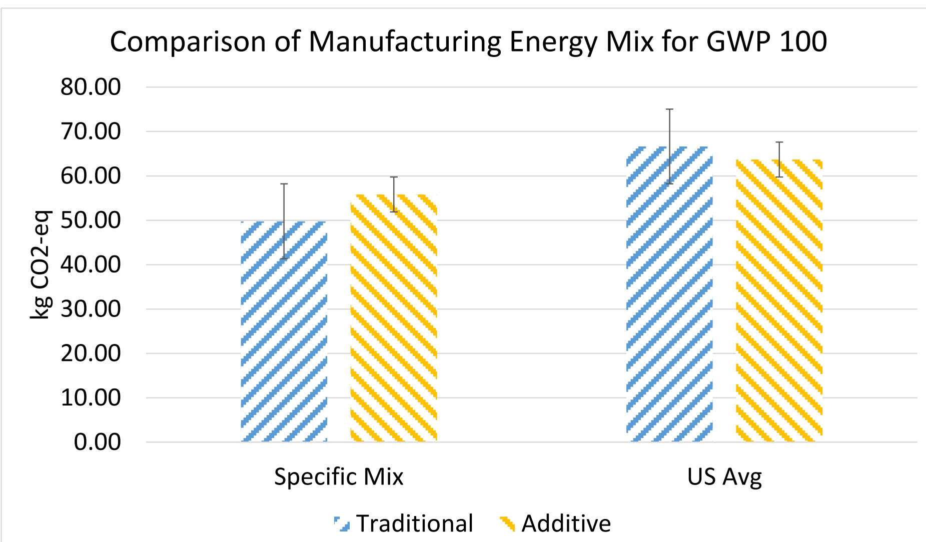


Figure 48: Energy-mix impacts on manufacturing for GWP 100

Values for the GWP100 energy-mix sensitivity for both manufacturing methods is reported in Table 36. Traditional manufacturing has the greater impact, though the difference between the two methods is slight at 4.5 percent. While the original results in the main analysis showed that additive had the greater impact.

Table 36: Energy Mix Sensitivity Manufacturing Comparison for GWP100

GWP100						
kg CO2-eq	Material	Process	Transport	Inspection	Packaging	Total
Traditional (Sensitivity U.S. Average Mix)	19.1	46.8	0.5	0.28	0.02	66.62
Traditional (Original Specific Location Mix)	18.4	32.0	0.5	0.19	0.02	49.77
Additive (Sensitivity U.S. Average Mix)	27.1	35.8	0.6	0.21	0.02	63.69
Additive (Original Specific Location Mix)	18.4	36.6	0.6	0.22	0.02	55.83

5.2.1.2 Input Material for Traditional-Manufacturing Sensitivity Analysis

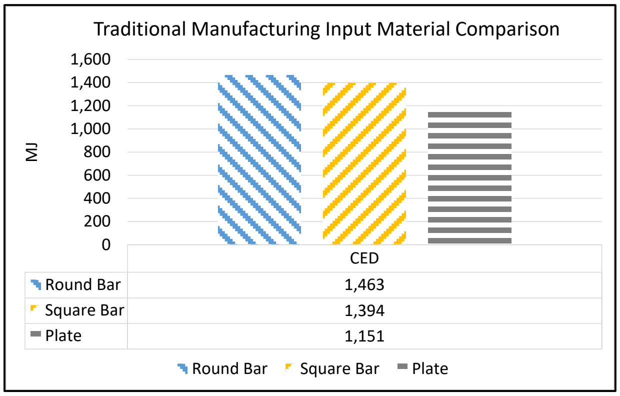
The original material used to make the machined bracket is a 1.75-in diameter bar of Inconel 718 cut to a length of 4.25 in. The material has a volume of 10.22 in.^{3} and a mass of 1.374 kg. In its raw form, it has significantly more material than the part; the machining process, therefore, generates a lot of waste as it cuts away from the stock bar. One analysis assumption is that LPT brackets can be manufactured from bar or plate stock that can be dimensionally closer to the final part, therefore, demanding less energy to machine and producing less waste. A sensitivity analysis was run for different input-material shapes that may be more representative of a production process.

The general part geometry is estimated to be approximately 1.25 by 1.125 by 4.125 in. The ideal raw input size is assumed to be approximately $^1/_8$ in. over the final part's outer dimensions (1.25 x 1.375 x 4.25 = 7.3047 in.^{3}), which is approximately 71.5 percent of the volume of the round-bar stock. Though this size might not be produced, a sensitivity analysis was conducted for reasonable sizes that might be available.

The potential standard square-stock size provided by the material supplier was 1.5 by 1.5 by 4.25 in. (9.563 in.^{3}). This is 93.6 percent of the volume of the round bar stock.

Inconel 718 can also be found in the form of plates, which are available in multiple sizes. A plate with a thickness of approximately 1.25 in. can be used to manufacture a number of brackets that can be cut into pieces that each measure 1.25 by 1.375 by 4.25 in. The resulting volume is 7.363 in.^{3} This is 72 percent of the original bar stock material.

Figure 49 shows the reduction of impacts for CED and GWP100, based on material inputs during the cradle-to–gate phases. Results show that by using a feedstock material that more closely represents the shape and size of the part geometry, that the cradle-to-gate impacts are reduced. The magnitude of the reduction for CED and GWP100 is approximately 21.4 percent and 22.3 percent respectively.



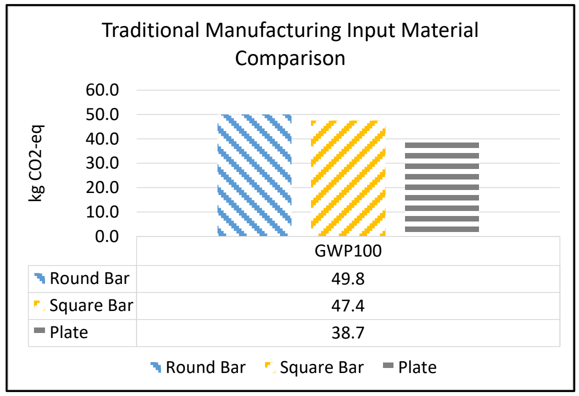


Figure 49: Sensitivity comparison for material input

5.2.1.3 Additive Input Material Utilization

This study assumes that the additive material process for powder production is able to produce 1 kg of powder for 1 kg of solid material input. Not all processes are 100 percent efficient and will always have some level of material or part loss. The following sensitivity analysis will explore these scenarios and the associated impacts.

For this sensitivity analysis, it is assumed that only 75 percent of the input material is converted to useable powder. This results in requiring an additional 0.25 kg of input material in order to achieve 1 kg of powder. Results indicate an overall increase of approximately 8 percent to the total impacts for the cradle-to-gate material and manufacturing process. The results for CED and GWP100 can be seen in Figure 50.

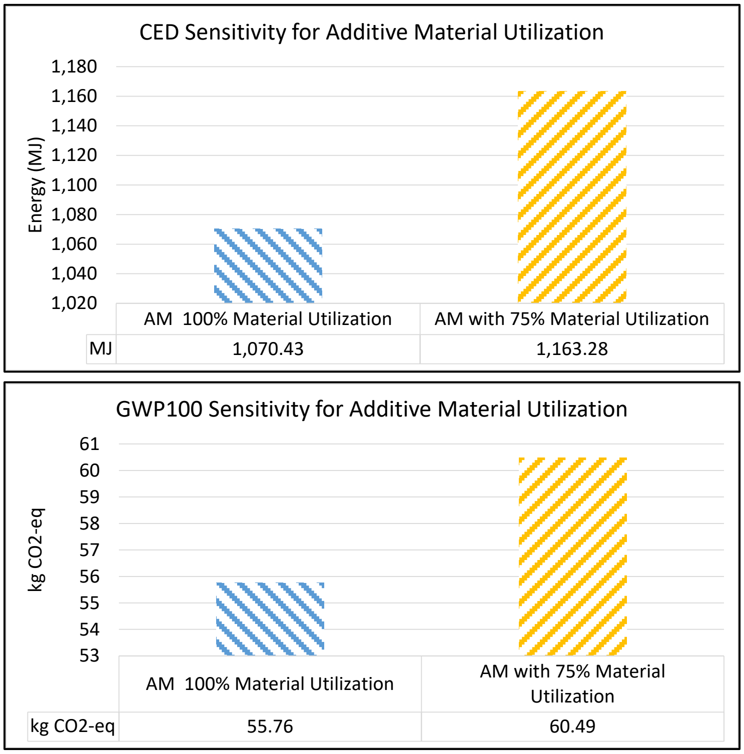


Figure 50: Sensitivity, additive-material utilization for CED and GWP100

5.2.1.4 Additive Part Defect and Material Sensitivity

As mentioned in the previous section, this sensitivity analysis investigates scenarios where material production and part manufacturing are less than 100 percent efficient, where potential losses may occur during specific processes.

In this sensitivity analysis, two different cradle-to-gate additive scenarios are evaluated and compared to the baseline additive and traditional cradle-to-gate results. In addition to the previous sensitivity analysis that looked at material utilization, this sensitivity analysis evaluated the 75 percent material utilization and 85 percent part-acceptance, where 15 percent of the parts made did not pass inspection. The other scenario evaluated if the powder material recovered from the previous build was used in this build along with the 85-percent part acceptance. Results for CED and GWP100 are shown in Figure 51 where using recovered material with 85 percent part-acceptance provides the least amount of impact. Conversely the combination of 75 percent material-utilization and 85 percent part-acceptance has the greatest impacts compared to the other scenarios. The ability of the additive process to recover the powder material for reuse can provide significant advantages to the life cycle impacts. Further study is required to better understand the material utilization factor and part acceptance rates, which was not part of this study.

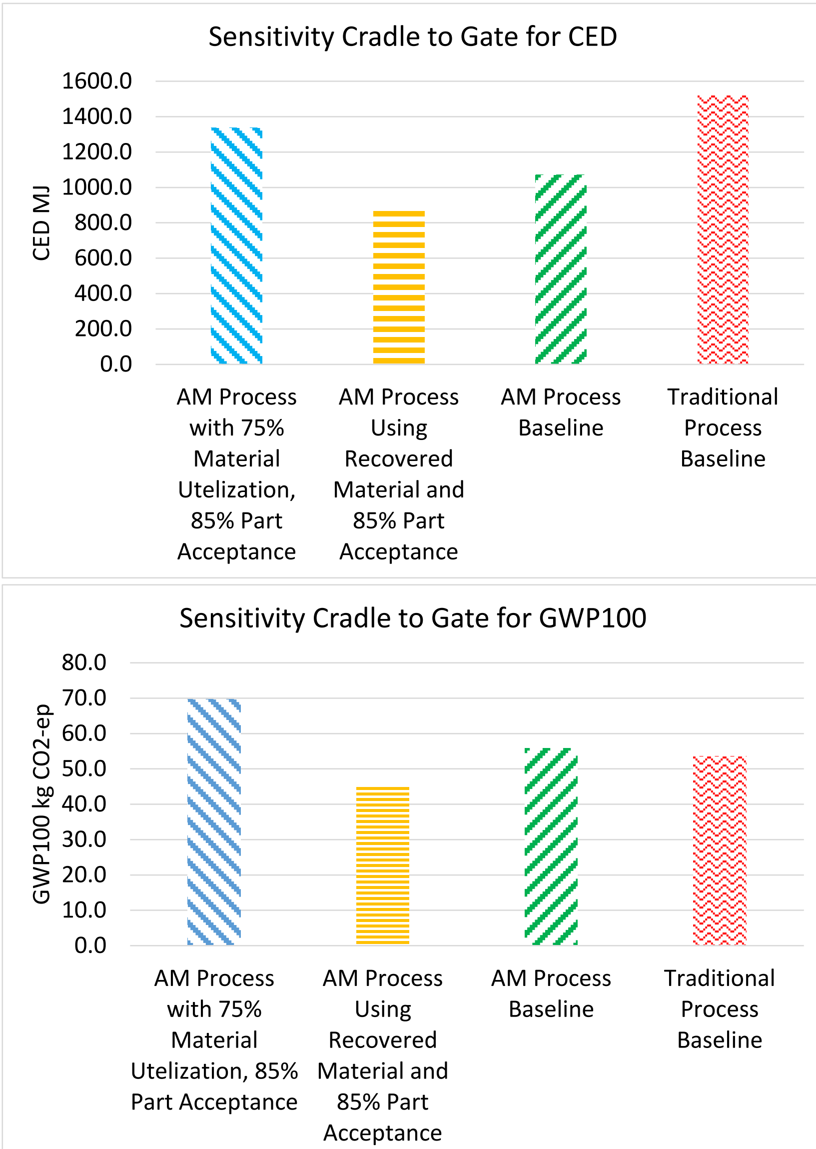


Figure 51: Sensitivity, Cradle-to-gate additive-material utilization for CED and GWP100

5.2.2 Uncertainty Analysis

The accuracy of any LCA-based decisions can often be limited if data variability and uncertainty are not incorporated into the decision. The goal of the uncertainty analysis is to understand how variation in the data and assumptions affect overall results and conclusions. Model variation can usually be depicted by a data distribution and by using traditional statistical methods, such as the Monte Carlo method, to understand uncertainties in LCA results.

SimaPro was used to perform a Monte Carlo analysis of the baseline case studies to understand how data uncertainty affected the comparison between the AM and traditional machining processes. Each scenario was run 1,000 times at a 95 percent confidence level. Approximately 65 percent of the Ecoinvent data contained uncertainty, and distributions were built for the machining energy based on the literature review.

These uncertainties further support the fact that conclusions cannot be explicitly drawn as to which manufacturing method is more sustainable in a generalized, universal way.

Uncertainty was evaluated for the three impact methods used in this study. Figure 52 shows uncertainty comparison between the AM and traditional manufacturing cradle-to-gate. Results indicate that 36 percent of the time AM will be less than traditional manufacturing. While 64 percent of the time AM will be greater than or equal to traditional. This does not give high confidence that one manufacturing method is more preferable over the other.

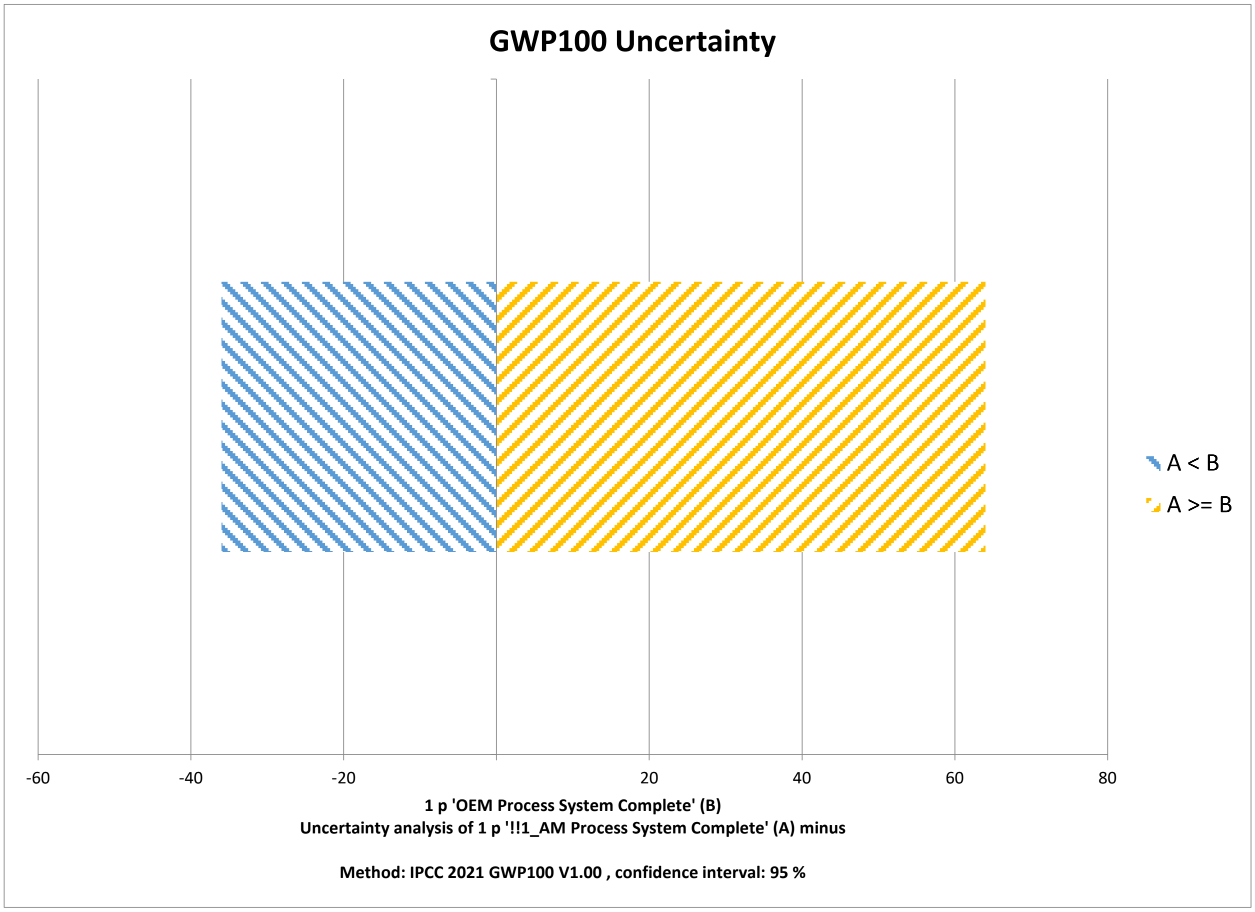


Figure 52: Uncertainty comparison for traditional and AM GWP100

For CED, the results indicate that 20 percent of the time traditional manufacturing is less than AM and 80 percent of the time it is greater than or equal to AM, shown in Figure 53.

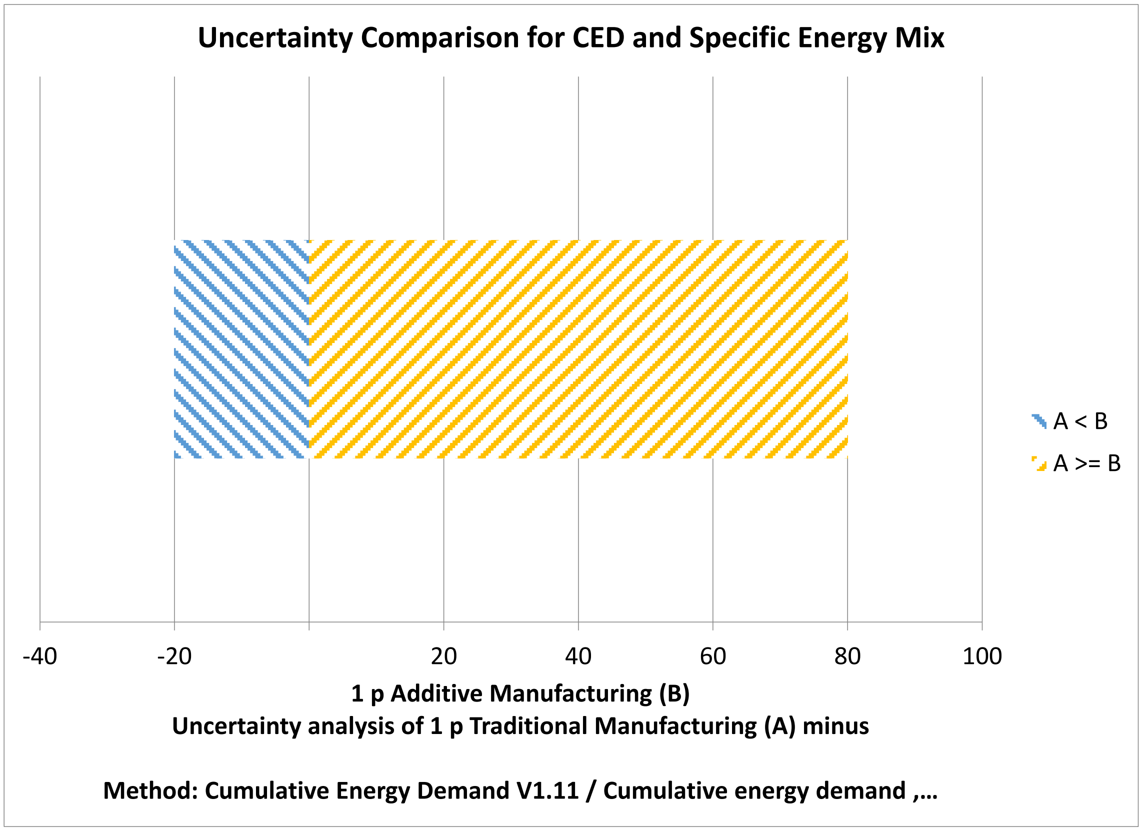


Figure 53: Uncertainty comparison for CED

Uncertainty results for the ReCiPe impact categories can be seen in Figure 54. Results for global warming appear to match results from the GWP100 previously discussed. While other impact categories within this method show similar results between the two manufacturing methods, there are several categories that do favor one over the other. Water consumption, mineral resource scarcity, human non-carcinogenic toxicity, as well as marine, freshwater, and terrestrial ecotoxicity, all show that the AM process impact will be greater than or equal to the traditional process 100 percent of the time. Conversely, the impacts of land use and ionizing radiation favor AM, as the uncertainty results indicate that AM will be less impactful than traditional 100 percent of the time.

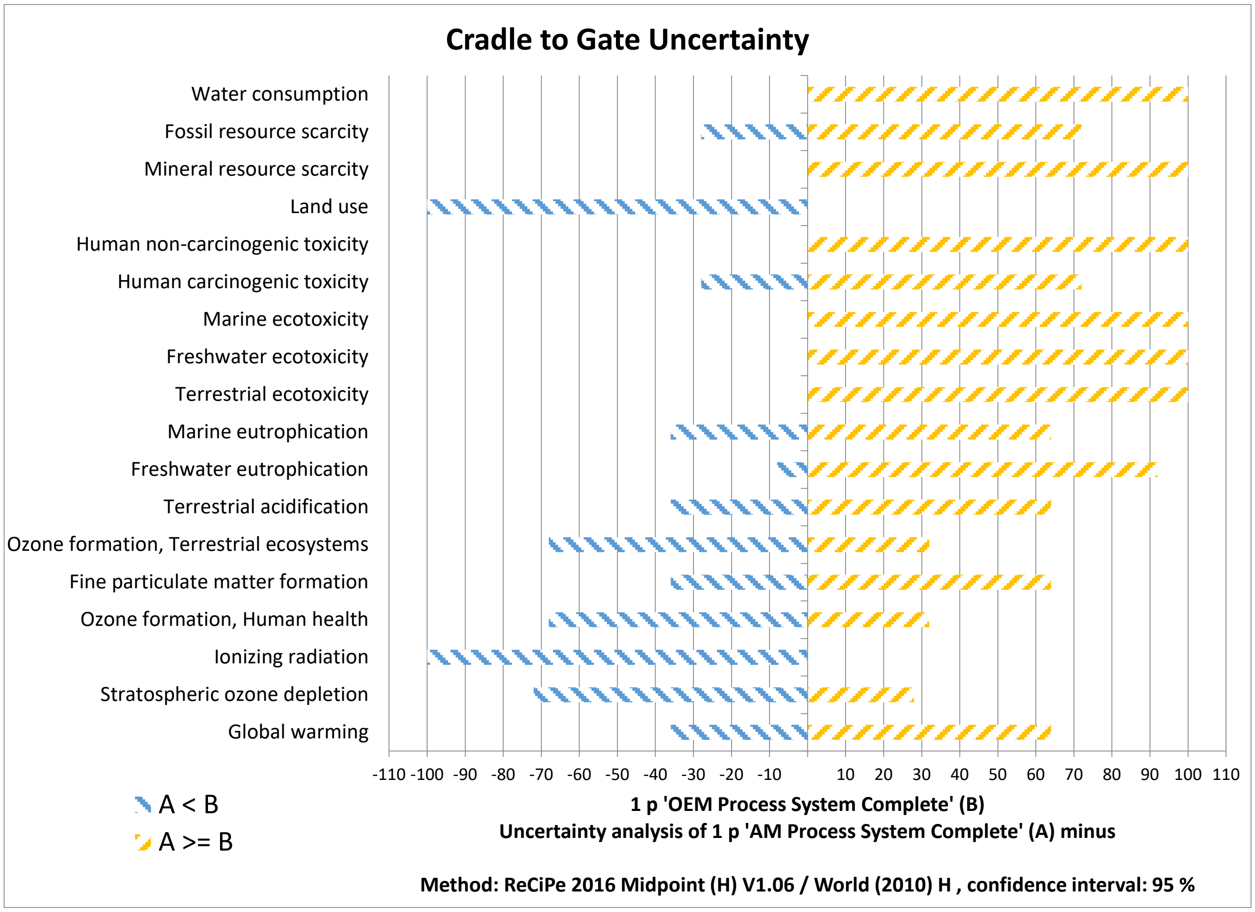


Figure 54: Uncertainty comparison for ReCiPe midpoint (H)

5.3 LPT Bracket Use-Phase Analysis

To better understand any fuel-efficiency benefits an AM-lightweighted LPT bracket might deliver, a model was developed to simulate an aircraft's operation. The model typified the weight reduction that a Boeing 767 would experience if its standard 24 LPT brackets were replaced with AM-produced versions. Using 4.17e-5 kg fuel/km per kg as a measurement of incremental weight, the simulation indicated that the lightweighted brackets would reduce the plane's fuel consumption by 0.0011 percent over a total lifetime flight distance of 93.3 million km.

The impacts for the base case studies, the reduced LPT-bracket weight, and the incremental affect (impact reduction) are shown in Table 37. Impact results for aircraft operation and kerosene production are derived from the ReCiPe 2016 V1.1 midpoint method for international aircraft operation of one person kilometer (pkm). For one pkm of travel uses 0.0288 kg of kerosene (aviation fuel). The impacts for one pkm were inputted into the ReCiPe method and the results reported for aircraft operation and fuel consumption. To correlate these impacts to a Boeing 767's lifetime fuel consumption scenario, they were divided by 0.0288 kg of fuel and multiplied by the calculated fuel consumption based on weight. This provides a scaled equivalent of the impact results for the simulated model.

Below is a description of the Ecoinvent unit process for intercontinental passenger aircraft travel from Ecoinvent.

- Operation, aircraft, passenger, intercontinental/person-km/RER U
  - Included processes: The inventory includes consumption of kerosene and direct emissions to air (gaseous emissions, particulate emissions, emissions of heavy metals)
  - Remark: Average fuel consumption and emission data caused by an intercontinental flight. The place of departure is Switzerland. In order to transform tonne kilometer (tkm) performance in passenger kilometer performance (pkm) each passenger is accounted for with a mass of 240 kg.
  - Geography: Data refers to average transport conditions of aircrafts departure from Swiss airports.

Table 37 shows the results of lifetime emissions for the 767-300ER. The first section shows the baseline case for flight using the traditionally manufactured bracket. The middle section shows results for the use of the additive bracket. The last section the difference between the base case and flight using the additive brackets.

Table 37: Baseline Flight Environmental Impacts and Impact Reductions Due to Weight Reduction for 767-300ER

	B767-300 Baseline Lifecycle impacts: 93.3M flight km			B767-300 with reduced LPT bracket Lifecycle impacts: 93.3M flight km			Impact reduction with AM LPT bracket Lifecycle impacts: 93.3M flight km		
Impacts for 1 person km, fuel consumption = 0.0288 kg/pkm	**Fuel Consumption(kg)**		**535,000,000**	**Fuel Consumption (kg)**		**534,994,130**	**Fuel Consumption Reduction (kg)**		**5870**
Impact category	Operation, aircraft, passenger, intercontinental/RER U	Kerosene, at regional storage/RER U	Total	Operation, aircraft, passenger, intercontinental/RER U	Kerosene, at regional storage/RER U	Total	Operation, aircraft, passenger, intercontinental/RER U	Kerosene, at regional storage/RER U	Total
Global warming	1.69E+09	2.81E+08	1.97E+09	1.69E+09	2.81E+08	1.97E+09	1.86E+04	3.09E+03	2.16E+04
Stratospheric ozone depletion	1.77E+02	3.41E+02	5.17E+02	1.77E+02	3.41E+02	5.17E+02	1.94E-03	3.74E-03	5.67E-03
Ionizing radiation	0.00E+00	3.25E+07	3.25E+07	0.00E+00	3.25E+07	3.25E+07	0.00E+00	3.56E+02	3.56E+02
Ozone formation, Human health	7.51E+06	9.63E+05	8.47E+06	7.51E+06	9.63E+05	8.47E+06	8.24E+01	1.06E+01	9.29E+01
Fine particulate matter formation	9.99E+05	8.64E+05	1.86E+06	9.99E+05	8.64E+05	1.86E+06	1.10E+01	9.48E+00	2.04E+01
Ozone formation, Terrestrial ecos	7.52E+06	9.74E+05	8.49E+06	7.52E+06	9.74E+05	8.49E+06	8.25E+01	1.07E+01	9.32E+01
Terrestrial acidification	3.23E+06	2.65E+06	5.88E+06	3.23E+06	2.65E+06	5.88E+06	3.55E+01	2.91E+01	6.45E+01
Freshwater eutrophication	0.00E+00	4.95E+04	4.95E+04	0.00E+00	4.95E+04	4.95E+04	0.00E+00	5.43E-01	5.43E-01
Marine eutrophication	0.00E+00	1.08E+04	1.08E+04	0.00E+00	1.08E+04	1.08E+04	0.00E+00	1.18E-01	1.18E-01
Terrestrial ecotoxicity	1.21E+09	3.63E+08	1.57E+09	1.21E+09	3.63E+08	1.57E+09	1.33E+04	3.98E+03	1.72E+04
Freshwater ecotoxicity	1.09E+04	2.21E+06	2.22E+06	1.09E+04	2.21E+06	2.22E+06	1.20E-01	2.42E+01	2.43E+01
Marine ecotoxicity	5.43E+05	5.95E+06	6.49E+06	5.43E+05	5.95E+06	6.49E+06	5.96E+00	6.52E+01	7.12E+01
Human carcinogenic toxicity	5.07E+06	9.37E+06	1.44E+07	5.07E+06	9.37E+06	1.44E+07	5.57E+01	1.03E+02	1.58E+02
Human non-carcinogenic toxicity	5.22E+06	1.01E+08	1.06E+08	5.22E+06	1.01E+08	1.06E+08	5.73E+01	1.11E+03	1.17E+03
Land use	0.00E+00	3.02E+07	3.02E+07	0.00E+00	3.02E+07	3.02E+07	0.00E+00	3.31E+02	3.31E+02
Mineral resource scarcity	0.00E+00	6.44E+05	6.44E+05	0.00E+00	6.44E+05	6.44E+05	0.00E+00	7.07E+00	7.07E+00
Fossil resource scarcity	0.00E+00	6.24E+08	6.24E+08	0.00E+00	6.24E+08	6.24E+08	0.00E+00	6.85E+03	6.85E+03
Water consumption	0.00E+00	3.59E+08	3.59E+08	0.00E+00	3.59E+08	3.59E+08	0.00E+00	3.93E+03	3.93E+03

Several impact categories were chosen to be represented graphically based on relevance to emissions due to combustion of fuel and aircraft flight, shown below.

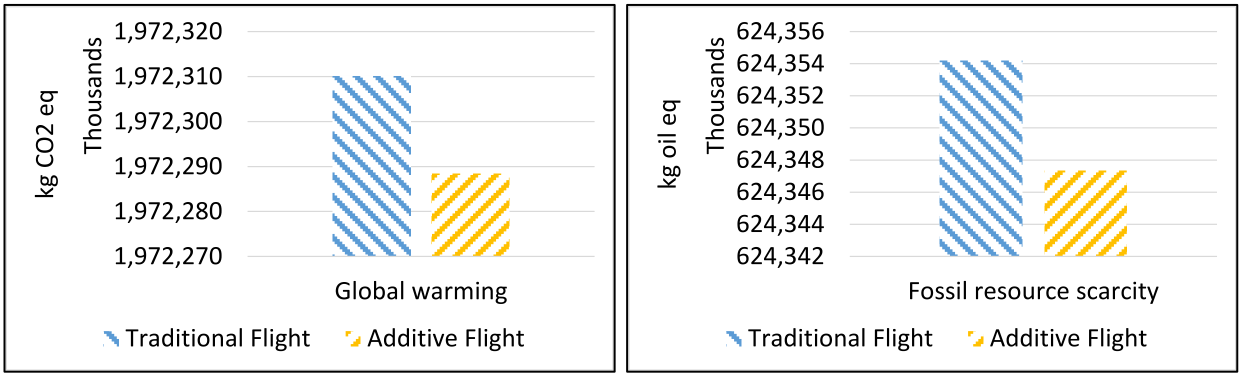


Figure 55: Impact comparison for aircraft operation for global warming (left) and fossil-resource scarcity (right)

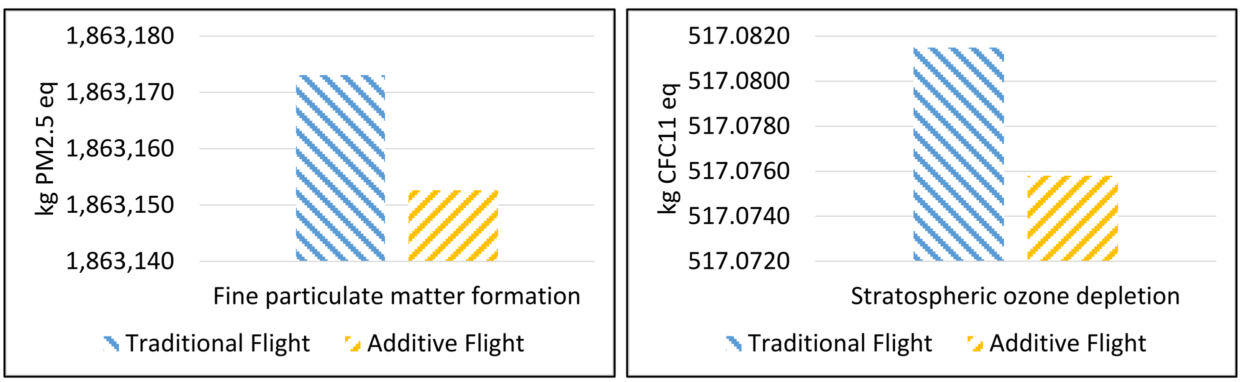


Figure 56: Impact comparison for aircraft operation for fine particulate matter formation (left) and stratospheric ozone depletion (right)

Flight-related impacts for the use phase of the 24 installed brackets were modeled separately to show the potential savings due to the use of lightweight materials. These savings include emissions related to the production of the fuel along with emissions from the aircraft operation. Results discussed in section 5.3 show the net results of the fuel savings based on the reduction in weight of the additively manufactured bracket. Table 37 for GWP100 indicate a lifetime savings of 21,565 kg CO2-eq for 125,000 flight hr.

The total GWP for the additive process is 1,340 kg CO2-eq. Based on the lifetime savings of 21,565 kg CO2-eq, the net savings would be approximately 20,225 kg CO2-eq for the additive LPT brackets.

Results for aircraft operation, which includes fuel consumption, shows that a Boeing 767 equipped with the lighter weight additive parts will have a GWP benefit. (See Figure 57.)

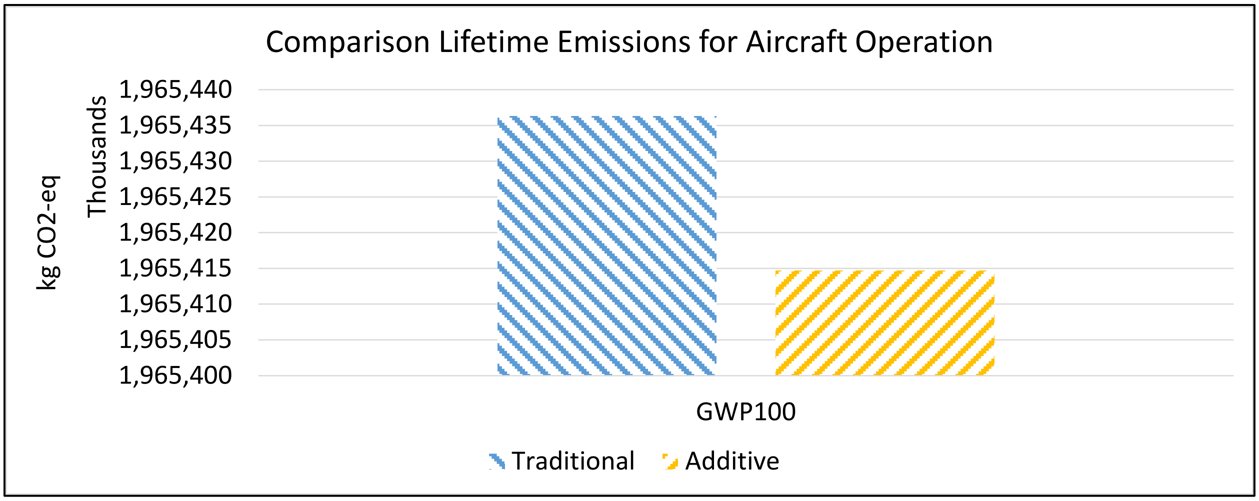


Figure 57: Aircraft operation GWP100 impact comparison between additive and traditional parts

In Figure 58, it can be seen that the use-phase impacts for aircraft flight significantly outweigh impacts related to the manufacture of 24 LPT brackets by either AM or traditional methods.

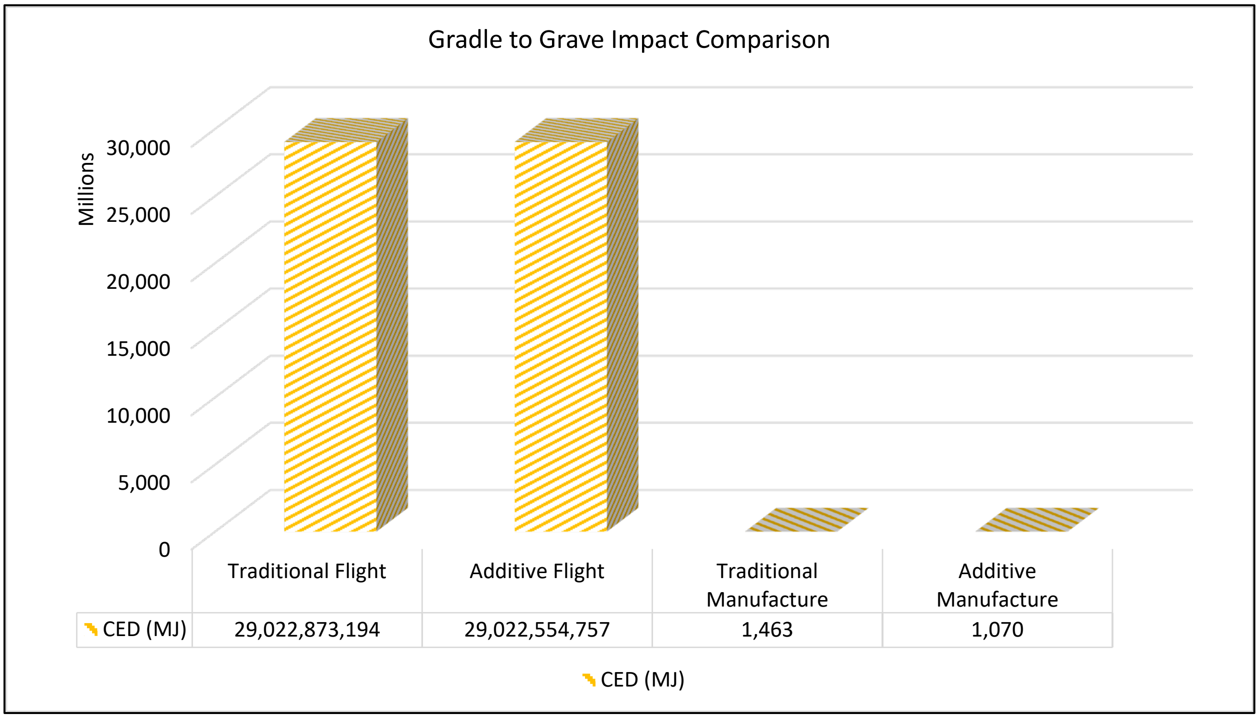


Figure 58: Cradle-to-grave impact comparison for CED

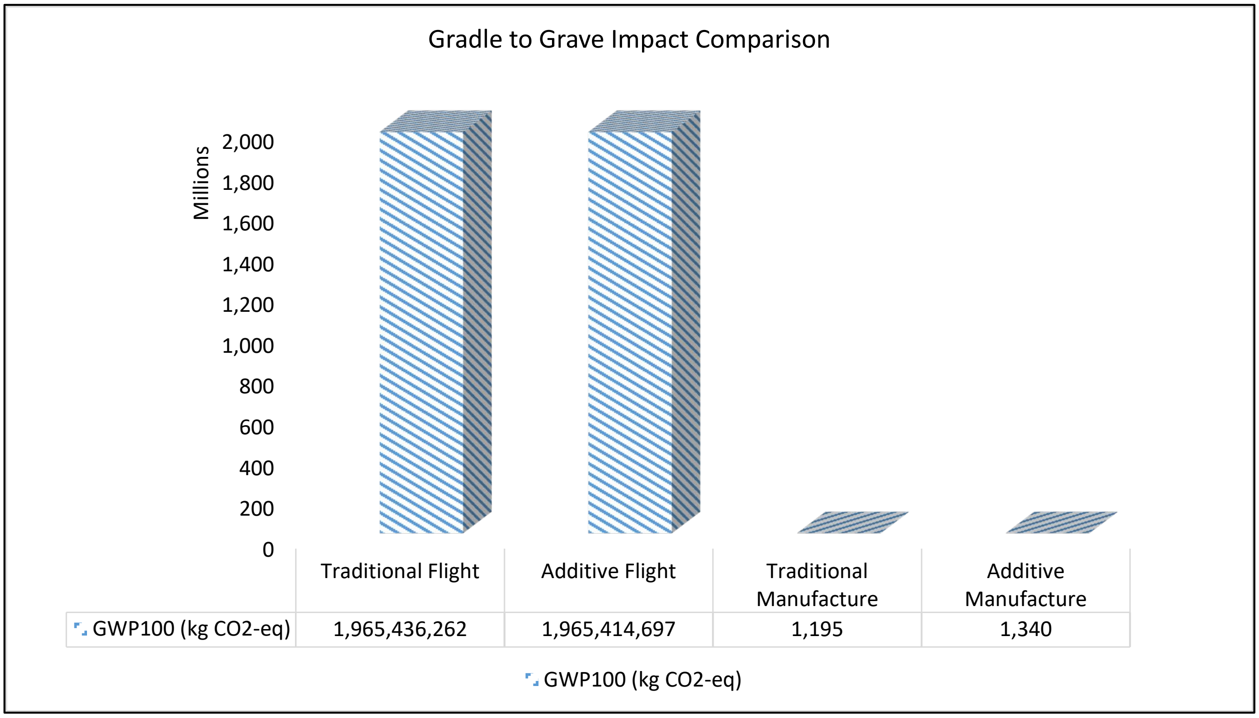


Figure 59: Cradle-to-grave Impact Comparison for GWP100

Regardless of the uncertainties related to the cradle-to-gate life cycle phase, the fuel savings due to weight reduction are definitive.

5.3.1 Uncertainty Analysis Full Life Cycle

To better understand the impacts associated with the full lifecycle, an uncertainty analysis was done to determine if there is any advantage to either manufactured LPT bracket. The uncertainty analysis for the cradle-to-gate (materials and part manufacturing) indicated that either method could be proved to be better than the other with at least 95 percent confidence. In this uncertainty analysis, the materials and manufacturing are combined with the use phase to determine if one method is in fact less impactful than the other.

For the analysis, we only consider the mass difference associated with the traditional and additive LPT brackets. All other conditions and variables related to the aircraft and flight are considered to be the same. The variability that can be associated with the entire fleet of aircraft are outside the scope and system boundary of this analysis.

The fuel use analysis in the previous section shows that the weight based fuel consumption will be reduced by 0.0011 percent over the total lifetime flight distance of 93.3 million km. The resulting fuel savings is determined to be 5870 kg of kerosene. This value can be converted to a representative flight distance in units of person-kilometer (pkm), and assuming 1 person, by dividing the 5870 kg of kerosene by 0.0288 kg/pkm of kerosene to get a net flight distance of 203,819 pkm. This can be considered the extra distance that the aircraft with the additive brackets could travel before the associated impacts would be the same as the aircraft with the traditional brackets. This net value is used in the uncertainty analysis to compare the aircraft with traditional brackets to the one with AM brackets.

Results of this uncertainty are shown in Figure 60 and Figure 61 for GWP100 and ReCiPe methods. These results show that with 100 percent confidence that the lighter additive bracket is in fact less impactful than the traditionally manufactured bracket over the full life cycle. The fuel savings over the life time of the aircraft outweighs the uncertainty associated with the cradle-to-gate phase of the life cycle.

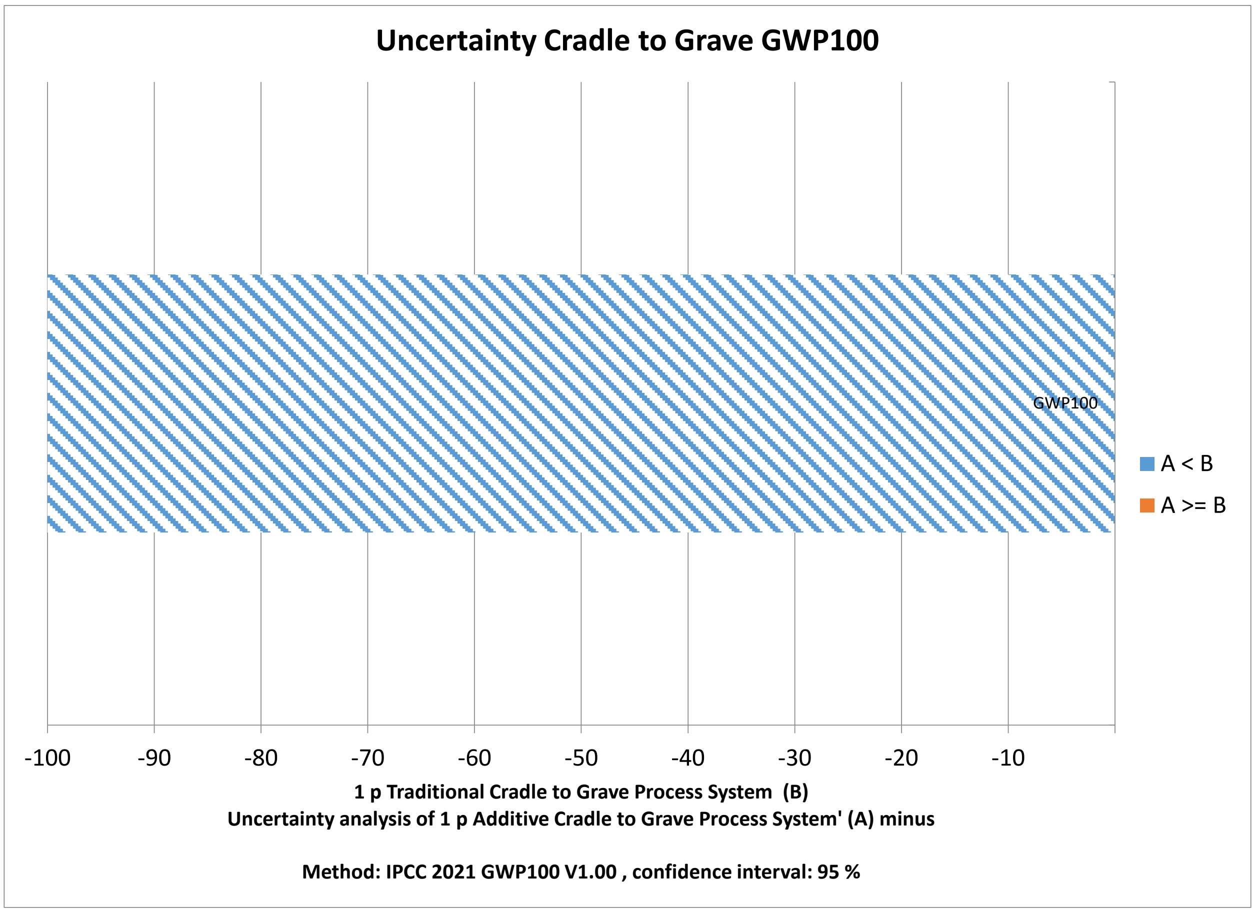


Figure 60: Uncertainty Cradle-to-grave (Full Life Cycle) for GWP100

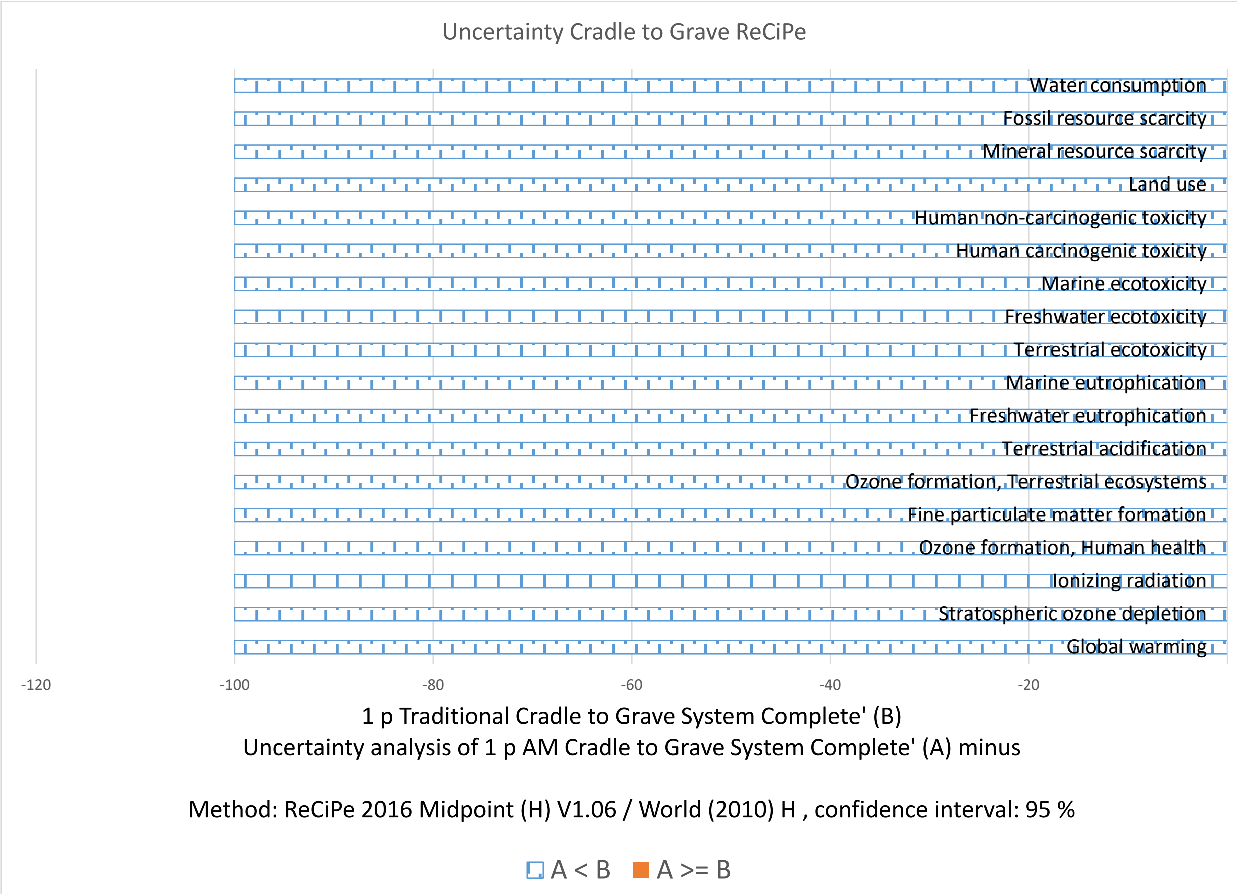


Figure 61: Uncertainty Cradle-to-grave (Full Life Cycle) for ReCiPe

6 Conclusion

The LCA captured in this report was conducted to give AMGTA a scientific understanding of AM as a sustainable alternative to traditionally machining LPT brackets for a Boeing 767 airplane. However, as has been shown, we were unable to conclusively make that determination from a process-orientated perspective. Taking this into account, GIS shifted from an assessment of the cradle-to-gate phases of an AM-made component to a closer analysis of how it might perform if it were installed on an aircraft.

Analysis of an AM-made bracket's use phase relied on a model of a long-haul Boeing-767 flight from London to Boston. We discovered through this simulation that a lighter weight version of the conventional LPT bracket would, over the course of the aircraft's lifetime, significantly lower its overall fuel consumption. The reduction in fuel use over that period would offset about 20,225 kg CO2-eq through the lightweighted design.

Based on these findings, the advantage that lightweighting affords in terms of sustainability is unambiguous. The next question asked was whether the climate impacts avoided through a lightweighted bracket design would outbalance those of the AM process itself, which this LCA showed could be greater than the conventional machining method in some cases (depending on local energy mix and raw-material characteristics).

This investigation found that the sustainability benefits of a lighter airplane that could be attributed to 24 LPT brackets—each weighing 51.6 percent less than the conventional versions—were more than enough to counterbalance those of the parts' cradle-to-gate life cycle. The conclusions presented in this report contribute to a larger body of research investigating the relative benefits and challenges of additive technologies in support of sustainable manufacturing. Most researchers agree that AM presents a unique pathway for reducing the mass of products, which will lower costs, emissions, and other impacts purely through the use of less material.

However, as this study shows, any application of AM must follow careful consideration of various factors influencing both the cradle-to-gate and use phases. For example, studies of light-metal aircraft components have shown that the weight advantages of AM compared to conventional vary tremendously depending on the specific geometries.[26]

Krishna et al. 2020 looked at comparing additive and subtractive manufacturing of aerospace components. They selected fused-deposition and CNC-machining for the comparison. The components are a bevel gear and a printed circuit board (PCB) support.[27] They found that energy consumption can be directly related to part-geometry complexity. In the case of a bevel gear, the impact of the additive process is almost 75 percent less than that for the traditional method. However, for a simple shape like the PCB support, that the traditional method has 50 percent less impact than the additive method. The authors also concluded that the overall reduction of material through AM will result in reduced impacts.

Another study concludes that it is not appropriate to label a manufacturing strategy as energy- and resource-efficient because of the heavy influence that properties of specific materials and processes exert on overall impacts.[28]

In general, it is assumed that the data and methods chosen are representative of the AM and traditional processes. Limitations exist for the material data, in particular production of the Inconel powder, which was not well documented in literature. Additional study could be done on the Inconel powder production process.

A study's completeness measures the portion of used data collected through primary means for each category in a unit process. In this study, actual material and process data were collected for the additively manufactured LPT brackets. Locations for manufacturing and material production were used when determining transport distances and related impacts.

Limitations related to the completeness of this study relate to the use of secondary data and literature values for the traditional machining energy. This was because the data provided is based on equipment power ratings and not actual energy use during operation.

This study looked at an isolated scenario of changing mass between two identical planes and potential fuel savings over the expected useful life. It is understood that other variations within the aircraft might outweigh the potential savings from a very small part.

The overall data quality is representative of the materials and processes analyzed for this study. Although, more data on the powder production process and machining energy would be beneficial.

Outlook

This study has shown that, in the case of LPT brackets for the Boeing 767, lightweighting should be considered as a viable design practice for improving the fuel efficiency of aircraft. Currently, the best available technology for realizing these designs is AM. This comes down to the much broader range of geometries that can be achieved through AM in comparison to traditional machining methods. It also allows an economy of material use that is inherent to a process that builds up, using only what is needed, rather than cutting away from solid stock.

Like other industrial sectors working to decarbonize, the aviation industry will need to employ many different strategies to meet the challenges stemming from climate change and resource depletion. This means strategically deploying a diversity of solutions, rather than a single “magic bullet.”

This study is intended to contribute to a growing body of scientific knowledge about AM, its potential and its limitations. Our hope is that this will allow aircraft designers to better understand how and where additive approaches can drive fuel and material efficiency.

In closing, conclusions cannot be drawn as to the benefit of one manufacturing method over another based on the results of this study. We found that variability in the following areas is high enough that the case-study conclusions cannot confidently be generalized to broader industry:

- manufacturing location
- energy mix
- the physical characteristics of raw materials (size and shape)

Yet, despite these limitations, the results of Phase 2 of this study clearly show that lightweighted LPT brackets can reduce a Boeing 767's lifetime carbon footprint. Importantly, we found that the reduction is such that, even if producing the bracket using AM levies more impacts than the conventional method during the cradle-to-gate phases, the resulting use-phase fuel savings more than make up for it.

As a result of this study, there are several takeaways and areas for future study. This work can be further expanded to better understand both the AM and traditional manufacturing processes and related energy use and waste generated. Also, better data for the production of Inconel powder is required to better compare the material impacts.

7 Appendix A: Material Data Sources

Table 38 Powder Chemistry Results at Sintavia

Element	036325-BK Meets AMS 5832	Measured	Method	Result
Manganese (Mn)	< 0.35	0.001	CRM BS 718-C	Conforms
Silicon (Si)	< 0.15	0.05	CRM BS 718-C	Conforms
Phosphorous (P)	< 0.015	0.003	CRM BS 718-C	Conforms
Sulfur (S)	< 0.003	0.002	ASTM E1941	Conforms
Carbon (C)	0.02 – 0.08	0.04	ASTM E1941	Conforms
Chrome (Cr)	17.00 – 21.00	18.4	CRM BS 718-C	Conforms
Molybdenum (Mo)	2.80 – 3.30	2.88	CRM BS 718-C	Conforms
Tantalum	< 0.05	0.005	CRM BS 718-C	Conforms
Aluminum (Al)	0.40 – 0.70	0.40	CRM BS 718-C	Conforms
Iron (Fe)	15.00 – 21.00	20.8	CRM BS 718-C	Conforms
Copper (Cu)	< 0.20	0.03	CRM BS 718-C	Conforms
Boron (B)	< 0.006	0.000	CRM BS 718-C	Conforms
Titanium (Ti)	0.85 – 1.15	0.92	CRM BS 718-C	Conforms
Cobalt (Co)	< 1.00	0.12	CRM BS 718-C	Conforms
Oxygen (O)	< 0.020	0.017	ASTM E1019	Conforms
Nitrogen (N)	< 0.020	0.013	ASTM E1019	Conforms
Nb (Cb) + Ta	4.75 – 5.50	4.95	CRM BS 718-C	Conforms
Nb (Cb)	4.75 – 5.50	4.94	CRM BS 718-C	Conforms
Nickel	50.00 - 55.00	51.6	CRM BS 718-C	Conforms
Nickel + Cobalt	50.00 - 55.00	51.72	CRM BS 718-C	Conforms
Note: Bi, Pb, Ag & Se		Not Tested	Not in CRM	Low Values for ICP

Certificate of Analysis & Certificate of Conformity

PRAXAIR SURFACE TECHNOLOGIES
1555 Main Street, Indianapolis, IN 46224

Product Name:	TruForm 718-35	Customer:		Ship Date:	11/06/2018
Praxair Spec:	036325-BK	Shipping Order #:	915038662	Printed Date:	06/NOV/2018
Item Number	036325-10KG	Customer PO #:	11006		
Lot Number:	96	Quantity:	1200	UM:	KG

All elements measured in weight percent unless otherwise specified. Sampling Method per ASTM B215.

Additional Tests	Test Method	Test Lab	Min	Max	Result	OK
Hausner Ratio	Calculation	Praxair		Report	1.21	Yes
Apparent Density	Test Method	Test Lab	Min	Max	Result	OK
Apparent Density per ASTM B212 (g/cm3)	ASTM B212	Praxair	3.80		4.13	Yes
Chemistry	Test Method	Test Lab	Min	Max	Result	OK
Silver	ICP-MS	NSL Analytical Services**		0.0005	<0.0005	Yes
Aluminum	XRF	Praxair	0.30	0.70	0.36	Yes
Boron	ICP-MS	NSL Analytical Services**		0.0060	<0.0010	Yes
Bismuth	ICP-MS	NSL Analytical Services**		0.00003	<0.00003	Yes
Calcium	ICP-MS	NSL Analytical Services**		0.01	0.00	Yes
Carbon (total)	Leco	Praxair	0.02	0.08	0.04	Yes
Cobalt	XRF	Praxair		1.00	0.12	Yes
Chromium	XRF	Praxair	17.00	21.00	18.82	Yes
Copper	XRF	Praxair		0.20	0.03	Yes
Iron	XRF	Praxair	15.00	21.00	18.38	Yes
Magnesium	ICP-MS	NSL Analytical Services**		0.01	0.00	Yes
Manganese	XRF	Praxair		0.35	0.07	Yes
Molybdenum	XRF	Praxair	2.80	3.30	3.01	Yes
Nitrogen	Leco	Praxair		0.020	0.014	Yes
Nb (Cb)	XRF	Praxair	4.75	5.50	5.20	Yes
Nb (Cb) + Ta	Calculation	Praxair	4.75	5.50	5.21	Yes
Nickel	By Difference	Praxair	50.00	55.00	52.81	Yes
Nickel + Cobalt	Calculation	Praxair	50.00	55.00	52.92	Yes

PST: 189297 C-116845

Spec ranges shown above in italics are target or nominal specifications only.

* indicates test is not required for routine acceptance.

** Denotes third-party materials testing laboratory accredited by Nadcap.

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Telefax (317) 240-2225
Toll-Free Telefax 1-800-234-6738 U.S.A

AS9100 Registered Quality System

Estimated uncertainty of measurement is available upon request. 1 of 4

11091-01 (Inco 718)

ROLLED ALLOYS

Rolled Alloys Inc.
711 Phoenix Lake Avenue Streamwood, IL
60107-2278
United States of America
Tel: 888-227-7862
Fax: 630-483-6279

Sales Order #	4231938-STR-1
Customer PO #:	20159

Certificate of Conformance

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United States of America

Ship To:

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& DESIGN LLC.
1528 ROPER MOUNTAIN ROAD
GREENVILLE, SC 29615
United States of America

In #	Item Description Dimensions	Specifications	Quantity	Mill Country of Origin	Heat # Tracer #
1	1-3/4" ROUND BAR CF 440C ANNEALED (+/-.003) P/N: SS-440C-RND-1.75"X90" JOB NUMBER(S): 11090-01 (0.25), 11090-02 (0.35), 11090-03 (0.4) 90.0 in Band Saw Random	Specs: See Test Report	1 pcs 60 lb	OUTOKUMPU STAINLESS, INC. United States of America	G27638 0621245US
2	1-3/4" ROUND BAR CG 718 ANNEALED (+/- .003) P/N: INCO718-RND-1.75X JOB NUMBER(S): 11091-01 (2) 4.25 in Chop Stroke Random	AMS 5662N	2 pcs 6 lb	ATI SPECIALTY MATERIALS United States of America	M9L31 0585253US

We hereby certify that the material supplied by Rolled Alloys on the above referenced purchase order was processed in accordance with the quality assurance program and procedures approved under our ISO 9001:2015/AS9100D certificate. The material was produced in compliance with the following revisions of our Quality Manual: Rev. F 1/14/2021, Rev. E 1/9/2020, Rev. D 6/1/2019, Rev. C 6/18/18, Rev. B 5/22/18, Rev. A 3/1/18, 3/28/15 (no letter), 3/7/14 (no letter), 1/22/14 (no letter), and 12/3/11 (no letter). Our records indicate that the material and test report(s) meet the requirements of EN 10204 for a Type 3.1 inspection certificate, and meet the requirements of the purchase order and applicable specifications. The certifications provided for the Tracer numbers above are authentic and true to the original document. Rolled Alloys QMS includes mechanisms and process controls for the prevention of counterfeit parts. Required documentation is on file, and is available for review upon request. The recording of false, fictitious or fraudulent statements or entries on this document may be punishable as a felony under federal statute. Unless otherwise specified, the materials supplied with this order did not come into known contact with mercury or other low melting point elements, radioactive materials, Polyclorinated Biphenyls (PCBs), nor undergo any weld repairs while under Rolled Alloys possession. (No mercury was used in the manufacturing of this product.) Rolled Alloys complies with the applicable requirements of the 2010 Dodd Frank Wall Street Reform and Consumer Protection Act, concerning Conflict Minerals. When applicable, Rolled Alloys complies with the requirements of AS6279 Standard Practice for Production, Distribution, and Procurement of Metal Stock. Products supplied by Rolled Alloys are compliant with EU Directive 2011/65/EU and 2015/863 (RoHS3). These articles have no intended release as outlined in the European Chemical Agency s Guidance on requirements for substances in articles (RIP 3.8), and there is no obligation to register them under REACH. Safety Data Sheets (SDS), formerly known a Material Safety Data Sheets (MSDS), are available at www.RolledAlloys.com. Products supplied by Rolled Alloys do not contain any significant amounts (does not exceed 0.1 Wt%) of the chemical compounds on the EU Candidate List of Substances of Very High Concern (SVHC).

ROLLED ALLOYS

Rolled Alloys Inc.
711 Phoenix Lake Avenue Streamwood, IL
60107-2278
United States of America
Tel: 888-227-7862
Fax: 630-483-6279

Sales Order # 4231938-STR-1
Customer PO #: 20159

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1528 ROPER MOUNTAIN ROAD
GREENVILLE, SC 29615
United States of America

Josh Messerole
Director of Quality

October 15, 2021
Date

ATI Specialty Materials
4374 Lancaster Highway, Richburg, SC 29729 US

CERTIFICATE OF TEST
Cert No.347595 Rev.1

Tina K. Colettiles
Certification Auditor
Date : October 31, 2019

Batch - 229969
Heat - M9L31
Ingot - 1

Customer Name & Address	Purchase Order No	Purchase Order Line No	Sales Order No	Sales Order Line No
Rolled Alloys PO Box 310 125 West Sterns Road Temperance MI 48182 US	0175299-STR	2	117635	2.1

Size (in)	Cross section	No Pcs	Weight (lbs)	Alloy
1.7500	Round	25	3,010	ATI 718™ Alloy

Specifications

Spec Name	Rev	Compliance Condition
AMS 5662	N	Compliant
AMS 5663	N	Capability

As Shipped Condition

Heat Treat	Heat Treat Cycles	Hot Work Type
Solution Annealed	Heat To 1750 F Hold 1 Hr(s) Air Cool	Rolled

Surface Finish
Centerless Ground

Remarks:
Cold Finished

Melt Method Details

Primary Melt	Facility	Address
Vacuum Induction Melt	ATI Monroe Operations	2020 Ashcraft Avenue, Monroe, NC 28110-5030 US

Remelt	Facility	Address
Vacuum Arc Remelt	ATI Monroe Operations	2020 Ashcraft Avenue, Monroe, NC 28110-5030 US

Conversion Method Details

Conversion Type	Facility	Address
Rolling	ATI Richburg Operations	4374 Lancaster Highway, Richburg, SC 29729 US

HEAT # M9L31
TRACER # 0585253US

Page 1 of 4 Cert No.347595 Rev.1

RIT | Golisano Institute for Sustainability

ATI Specialty Materials-4374 Lancaster Highway,Richburg, SC 29729 US

Batch - 229969 Heat - M9L31 Ingot - 1

CHEMISTRY

Sample Source			Heat Avg
Test Facility			ATI Monroe Operations
Elements	UOM	Method	Average
C	%	CS	0.03
Mn	%	XRF	0.07
Si	%	XRF	0.06
P	%	XRF	0.008
S	%	CS	<0.0003
Cr	%	XRF	17.95
Ni	%	XRF	53.76
Mo	%	XRF	2.89
Nb	%	XRF	5.42
Ti	%	XRF	1.00
Al	%	XRF	0.48
Co	%	XRF	0.23
B	%	OES	0.004
Cu	%	XRF	0.04
Fe	%	XRF	Bal

Remarks:
CS = Combustion/IR Detection
OES = Spark Optical Emission
XRF = X-Ray Fluorescence

Sample Source			Ladle
Test Facility			ATI Monroe Operations
Elements	UOM	Method	
Pb	PPM	WET	<1
Bi	PPM	WET	0.1
Se	PPM	WET	<0.5

Remarks:
WET = Graphite Furnace Atomic Absorption - Se
WET = Mass Spectroscopy - Pb, Bi

Remarks:
Test Methods: C/S/O/N = ASTM E1019 (2018); XRF = ASTM E572 (2013), ASTM E1085 (2016), ASTM E2465 (2013); OES = ASTM E415 (2017), ASTM E1086 (2014), ASTM E3047 (2016); ICP = ASTM E2594 (2009/2014); Mass Spec. = ASTM E2823 (2017); GFAA = ASTM E1834 (2011)

MECHANICAL

Test Specimen Heat Treatment(s)

Plant: 1750F,1hr,AC
Laboratory: 1325F,8hrs,FC,100,TOTAL AGE 18 HRS - 1150F,8hrs,AC

Tensile

Piece ID	Sample Direction	Sample Location	Test Temperature	Ultimate Strength (ksi)	.2% Yield Strength (ksi)	4D-Elongation (%)	Reduction of Area (%)	Initial Gage Length (in)	Initial Diameter (in)	Crosshead Speed	Strain Rate (in/in/min)	Test Facility
1	L	MR	ROOM	207.8	177.2	21.2	38.8	1.0000	0.253	0.05	0.003	Acuren

Remarks:
Elongation determined after fracture.
ASTM E8/E8M (2016a)

Piece ID	Sample Direction	Sample Location	Test Temperature (F)	Ultimate Strength (ksi)	.2% Yield Strength (ksi)	4D-Elongation (%)	Reduction of Area (%)	Initial Gage Length (in)	Initial Diameter (in)	Crosshead Speed	Strain Rate (in/in/min)	Test Facility
1	L	MR	1200	171.0	140.0	36.4	67.8	1.0000	0.252	0.05	0.005	Acuren

Remarks:
Elongation determined after fracture.
ASTM E21 (2017)

HEAT # M9L31
TRACER # 0585253US

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Cert No.347595 Rev.1

8 Appendix B: AM Primary Data

Top Process		Per Unit		
Process description	**Item**	**Value**	**Units**	**Comments, assumptions, and data source**
AM Process M400	Bracket			https://na.eos.info/Equipment/Metal-Platforms/EOS-M-400
	Inconel 718 Powder	0.13095	kg	Inconel Powder input into AM system used for build (5.5 kg)
	Build Plate	1.90476	kg	What material is this?
	Process Energy	30.81	kwh	Per part energy 42 parts, 52 hour build time (24.885 kwh) **Use FL energy mix from EIA.gov**
Waste Powder	Waste powder to landfill	0.004286	kg	0.180 kg of powder wated per 42 bracket build Nickel is highly recoverable and can be sived many times before it is no longer useful
Depowder and Inspection				
Waste Powder	Waste powder to landfill	0.010952	kg	0.46 kg powder removed and sent to landfil
	Compressed air use	11.42	cuft	0.724 Mpa (0.017238 Mpa/part) 1 hour operation
Stress Relief		1		GM Furnace, HVF-401B
argon	argon Liters per cycle	1.821	L	16995 per build (42 parts) on plate (2.536kg)
Energy	Process Energy	0.5283	kwh	9 hours @ 547.95 kwh
Remove From build Plate				
Wire EDM Energy	FL Grid Electricity Mix	1.607	kwh	Mitsubishi Electric EDM, WBI-Series WEDM
EDM Wire Material		0.048	kg	
Compressed Air		19.28	cuft	Make and Model: Kaiser AS30 Flow rate: 124 CFM @125 PSIG (max working pressure)

Top Process		Per Unit		
Process description	**Item**	**Value**	**Units**	**Comments, assumptions, and data source**
Waste Material		0.0188	kg	
EDM Radius Cut				
Wire EDM Energy		10.125	kWh	
EDM Wire Material		0.343	kg	
Compressed Air		121.5	cuft	Make and Model: Kaiser AS30 Flow rate: 124 CFM @125 PSIG (max working pressure)
Waste Material		0.0365	kg	
Temporary Part Marking				
Label Material	Plastic bags 7x4			
Debur by hand				
Overhead energy			kwh	2 hours of time
Waste Material		0.0047	kg	
Finishing				Empire Blaster, PF2636
Blast Media		0.7583	kg	
Compressed air		90	cuft	
Energy		0.075	kwh	
Waste Material		0.000476	kg	
Visual Inspecton				
Energy				Overhead
Dimensional inspection				
Compressed Air		5	cuft	2 hours
Energy		0.1786	kwh	
Shipping				Shipping to and from radiographic inspection (round trip)
Transport		4.8	miles	9.6 round trip = 15.45km

Top Process		Per Unit		
Process description	Item	Value	Units	Comments, assumptions, and data source
Radiographic Inspection				
Energy		0.1	kwh	
Receiving				
Packaging				7x4 bubble wrap bags (qty 42) 1 8x10x12 Cardboard Box Plastic Wrap

9 Appendix C: Traditional Manufacturing Primary Data

Top Process	Per Unit		
Process description	Value	Units	Comments, assumptions, and data source
CNC Lathe			Faced and cut to length
Energy	4.5	kwh	
Scap material	Minimal	kg	
Compressed Air	1.26	cuft	2 second blast of air
Coolant	0.0013	gal	assumes 25 days per month, 16 hours per day (2 shifts) and 9 machines utelizing one 55gallon drum of coolant
CNC Mill 750			The faced material is now ready to be milled to fit our fixturing. A dovetail feature is added to the bottom of the bracket to mount on our intended fixturing setup for the 5 Axis Operation. § Mill machines use coolant which is injected from a 55 gallon drum that is fed with water to create coolant for the milling machines. However, that drum lasts approximately 2 months and is shared between 9 machines. We did not have a way to gauge water/coolant consumption to 1 part.
Energy	4.8	kwh	
Scap material	0.4322	kg	
Compressed Air	1.26	cuft	2 second blast of air
Coolant	0.0019	gal	assumes 25 days per month, 16 hours per day (2 shifts) and 9 machines utelizing one 55gallon drum of coolant

Top Process	Per Unit		
Process description	Value	Units	Comments, assumptions, and data source
CNC Mill 200/5 Axis			The 5 Axis operation is now underway. Keep in mind that IMD does not have a TRUE 5 Axis therefore we will have to use an educated guess to the final features our 5 axis cannot perform. use this for the analysis (1700 mean with 1200 and 2750 as sensitivity thresholds) and support this with the brown work. Flood cutting Range of Machine Energy Machine specific energy (j/mm3) 1200 1700 2750 mj/kg 145.9854 206.8127 334.5499 AMGTA values. If you use 20.81 hour machining time, with 11KW (based on max continuous spindle power) you get 1063 MJ/kg. I'm not sure that it makes sense to use this in the sensitivity analysis, but it might be more satisfying to the customer – although it's still almost 50 percent lower than what they suggested. For the volume removed (and 20 hour processing time) the average removal rate is 1.3 mm3mm/s, which is approximately in the middle of the testing range for the Liu paper, so maybe not so unreasonable. Liu paper also has data on tool life (they estimate at 26 min (based on wear), and cutting fluid use (not sure what assumptions this is based on). Tool life is important in the overall, cutting fluid less so.
Energy	398.3	kwh	
Scap material	0.7753	kg	
Compressed Air	1.26	cuft	Quincy QGS-10 17 TMD, 10 HP Rotary Screw Air Compressor, 38 CFM @ 125 PSI, 120 Gallon Air Tank & Air Dryer 208-230/460-Volt, 3-Phase
Coolant	0.152	gal	assumes 25 days per month, 16 hours per day (2 shifts) and 9 machines utelizing one 55gallon drum of coolant
Wire EDM			The Wire EDM Operation completes the part by adding the radius to the bottom of the bracket.
Energy	8.8	kwh	
Scap material	0.0357	kg	
Compressed Air	162	cuft	

Top Process	Per Unit		
Process description	**Value**	**Units**	**Comments, assumptions, and data source**
Media			Media blast part using Aluminum Oxide Glass Bead.
Energy	1.4	kwh	
Scap material	0.0077	kg	
Blast Meida	0.227	kg	Aluminum oxide
Compressed Air	30	cuft	2 minutes
Part Marking			Part Marking is the last step in the process before FPI begins.
Energy		kwh	
Shipping to ATS			Bracket is moving to Applied Technical Services for FPI Inspection
Distance Traveled	8.2	mi	Round trip (4.1 miles one way) (13.196km)
FPI			
CMM Inspection			
Energy	1.4	kwh	

10 Critical Review Letter of Compliance and Committee Approval

Highly Restricted

EarthShift Global
ADVANCING YOUR SUSTAINABILITY

Final Critical Review Statement

Date	28-Mar-23
Title of the study	**Comparative LCA of a Low Pressure Turbine Bracket by Two Manufacturing Methods**
The commissioner of the LCA study	AMGTA
The practitioners of the LCA study	Allen Luccitti Golisano Institute for Sustainability (GIS) Rochester Institute of Technology (RIT)
The exact version of the report to which the critical review statement belongs	28-Mar-23
The reviewer(s) or, in the case of a panel review, the panel members, including the identification of the panel chairperson	Panel Chair: Lise Laurin, EarthShift Global, LLC; provided input into the LCA process and adherence to ISO 14040 and ISO 14044
	Steven Diantzikis reviewed the CNC process to ensure the assumptions and data used were reasonable and the boundaries were appropriate.
	Harsha Malshe of DSG Consulting, reviewed the additive process to ensure the assumptions and data used were reasonable and the boundaries were appropriate.
	Zeynab Yousefzadeh of EarthShift Global reviewed the metallurgy and powdering processes to ensure the assumptions and data used were reasonable and the boundaries were appropriate.
Description of the review process, including information on:	The chair provided the LCA expertise and relied on the panel members for subject-matter expertise. Each panel member reviewed the report and provided their comments to the chair who shared them with the practitioners.
• whether the review was performed based on ISO 14044:2006, 6.2 or 6.3;	The review was based on ISO 14044:2006, section 6.3
• whether the review was performed in parallel or at the end of the study;	The study was performed at the end of the study
• whether the review included or excluded an assessment of the LCI model;	The committee reviewed the unit processes but did not review the SimaPro model.
• whether the review included an analysis of individual data sets;	The committee reviewed the unit processes but did not review the SimaPro model.
Description of how comments were provided, discussed and implemented;	Comments were provided both via Word Documents and verbally and discussed through web call and email. This included two rounds of comments.
Panel Decision:	The study meets current requirements for ISO 14044
Applicability of Study Results:	Limitations of the study are primarily that the conventional manufacturing process could be performed many different ways with varying impact. The major

	conclusion, however, revolves around potential fuel savings and that would not change with different conventional techniques.

Critical Review Summary

A Critical Review of Comparative LCA of a Low Pressure Turbine Bracket by Two Manufacturing Methods has been carried out by Lise Laurin, CEO of EarthShift Global and a panel of experts representing interested parties. The review has been carried out according to ISO 14044:2006 for a comparative assertion LCA report prepared for third party review. This review statement in no way endorses the products mentioned in the study.

The panel critically reviewed this LCA study and supporting documents to determine if the following conditions were met:

- The methods used to carry out the LCA are consistent with the International Standards (ISO 14040 and 14044);
- The methods used to carry out the LCA are scientifically and technically valid;
- The data used are appropriate and reasonable in relation to the goal of the study;
- The interpretations reflect the limitations identified and the goal of the study; and
- The study report is transparent and consistent.

To conduct this critical review, after a review of adherence to ISO 14044, the chair of the committee shared the study and specific technical questions outside of her expertise with the panel review members. The panel members reviewed the study and commented on both what they found in the study and the questions of the review chair. Comments were reviewed to ensure they were appropriate for an ISO 14044 review, collated and shared with the practitioner. The study went through two rounds of revisions based on committee comments. After the final round there were only two reservations which are common to many published studies and this final review statement was prepared.

Final Review Statement

All the issues raised by the reviewers have been addressed in the LCA report, and the reviewers assess that overall the LCA study is in compliance with and fulfills the requirements in ISO 14040 and 14044 for studies used for publication.

Are the methods used to carry out the LCA consistent with the international standards (ISO 14040, 14044)?

The reviewers find that the study is consistent with the ISO LCA standards. The methodology is clearly described, and all modeling assumptions are documented and explained.

Are the methods used to carry out the LCA scientifically and technically valid?

The reviewers find that the methods used to carry out the LCA are scientifically and technically valid.

Are the data used appropriate and reasonable in relation to the goal of the study?

The reviewers find that the use of data is appropriate and reasonable in relation to the goal of the study.

Do the interpretations reflect the limitations identified and the goal and scope of the study?

The reviewers find that the interpretations reflect the limitations identified and the goal of the study.

Is the study report transparent and consistent?

The reviewers find that the study report is transparent and consistent.

Panel Chair

Lise Laurin
CEO, EarthShift Global

11 Endnotes

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