

**T.R.**  
**GEBZE TECHNICAL UNIVERSITY**  
**INSTITUTE OF ENERGY TECHNOLOGIES**

**UTILIZING ADDITIVE MANUFACTURING FOR DESIGNING  
AEROSPACE COMPONENTS VIA TOPOLOGY OPTIMIZATION**

**AHMET KAN ZAYİM**

**A THESIS SUBMITTED FOR THE DEGREE OF  
MASTER OF SCIENCE APPLIED PROPULSION SYSTEM  
DESIGN & ENGINEERING FOR AEROSPACE TECHNOLOGIES**

**GEBZE**  
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**THESIS SUPERVISOR  
PROF. DR. OSMAN SAİM DİNÇ**

**GEBZE**

**2023**



## YÜKSEK LİSANS JÜRİ ONAY FORMU

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### ONAY

Gebze Teknik Üniversitesi Fen Bilimleri Enstitüsü Yönetim Kurulu'nun  
...../...../..... tarih ve ...../..... sayılı kararı.

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## SUMMARY

Additive Manufacturing (AM) is rapidly becoming widespread in many industries and starting to be an alternative to traditional production methods with its advantages. AM will not be a production method on its own, but with the increasing variety of materials, it plays a very important role in the production of especially complex shapes.

As AM technology develops, the importance of Topology Optimization (TO) softwares also increases. While lighter and stronger parts could be designed with TO, a mathematical method that optimizes the arrangement of materials within a given design space for a given set of loads, boundary conditions and constraints, some of these designs could not be in a geometry to be manufactured with traditional manufacturing methods. Nowadays, mechanical design engineers can make more use of TO opportunities with AM.

The aim of this study is to analyze the bracket parts used in a turbodiesel aviation engine in a way that can be produced with AM. Within the scope of the study, first of all, static structural analysis of the brackets was made with their current condition. Then, TO analyzes were made as two bracket pieces as one piece. Besides it was expected that the weight of the part would decrease without affecting its strength. Static structural analysis was performed again for the purpose of comparison on the obtained optimized part. The analysis of the brackets was conducted via ANSYS Workbench.

As a result of the study, a lighter, easily mountable, via AM can be manufactured, one-piece bracket design has been made instead of two parts, and it has been shown that the design does not have a weakness in terms of strength compared to the non-optimized geometry.

**Key Words: Additive Manufacturing (AM), Topology Optimization (TO), Design for Additive Manufacturing (DfAM), Turbodiesel Aviation Engine Bracket**

## ÖZET

Katmanlı İmalat (AM), birçok endüstride hızla yaygınlaşmakta ve avantajlarıyla geleneksel üretim yöntemlerine alternatif olmaya başlamaktadır. Tek başına bir imalat yöntemi olmayacaktır fakat her geçen gün artan malzeme çeşitliliğiyle birlikte, özellikle karmaşık şekillerin üretiminde oldukça önemli rol almaktadır.

AM teknolojisi geliştikçe Topoloji Optimizasyon (TO) programlarının önemi de artmaktadır. Belirli bir yük, sınır koşulları ve kısıtlamalar kümesi için belirli bir tasarım uzayı içinde malzemelerin düzenlenmesini optimize eden matematiksel bir yöntem olan TO ile daha hafif ve daha güçlü parçalar tasarlanabilirken, bu tasarımlardan bazıları geleneksel imalat yöntemlerine uygun geometrilere değillerdir. Günümüzde mekanik tasarım mühendisleri AM ile birlikte TO imkanlarından daha fazla yararlanılabilmektedir.

Bu çalışmanın amacı bir turbodizel havacılık motorunda kullanılan braket parçalarının AM ile üretilebilecek bir şekilde TO analiz çalışması yapılmasıdır. Çalışma kapsamında braketlere öncelikle mevcut durumlarıyla mukavemet analizi yapılmıştır. Sonrasında iki adet braket parçası, tek parça olacak şekilde TO analizleri yapılmıştır. Aynı zamanda parçanın ağırlığının düşmesi fakat dayanımının azalmaması beklenmiştir. Elde edilen optimize parçaya karşılaştırma amaçlı tekrar mukavemet analizi yapılmıştır. Braketlerin analiz çalışması ANSYS Workbench aracılığıyla yapılmıştır.

Çalışma sonucunda daha hafif, kolay montajlanabilir, AM ile imal edilebilir, iki parça yerine tek parça olan braket tasarımı yapılmıştır ve tasarımın, optimize edilmemiş geometriye göre mukavemet açısından bir eksiğinin olmadığı gösterilmiştir.

**Anahtar Kelimeler: Katmanlı İmalat, Topoloji Optimizasyonu, Katmanlı İmalat için Tasarım, Turbodizel Havacılık Motoru Braketi**

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## LIST OF ABBREVIATIONS AND ACRONYMS

<b>Abbreviations</b>	<b>Explanations</b>
AM	: Additive Manufacturing
ANSYS	: Analysis Of Systems
ASTM	: American Society For Testing And Materials
AW-DED	: Arc Wire Directed Energy Deposition
BJ	: Binder Jetting
CAD	: Computer-Aided Design
CFM	: Commercial Fan Motor
DED	: Directed Energy Deposition
DLP	: Digital Light Processing
DMLS	: Direct Metal Laser Sintering
EB-DED	: Electron Beam Directed Energy Deposition
EBM	: Electron Beam Melting
EB-PBF	: Electron Beam Powder Bed Fusion
FAA	: Federal Aviation Administration
FDM	: Fused Deposition Modeling
GE	: General Electric
GMA-DED	: Gas Metal Arc Direct Energy Deposition
GTA-DED	: Gas Tungsten Arc Direct Energy Deposition
ISO	: International Organization For Standardization
LD-DED	: Laser Direct Directed Energy Deposition
LEAP Engine	: Leading Edge Aviation Propulsion Engine
LMD	: Laser Metal Deposition
LOM	: Laminated Object Manufacturing
L-PBF	: Laser Powder Bed Fusion
LW-DED	: Laser Wire Directed Energy Deposition
MJ	: Material Jetting
MJM	: Multi-Jet Modelling
NASA	: National Aeronautics and Space Administration
PA-DED	: Plasma Arc Direct Energy Deposition

PBF	:	Powder Bed Fusion
PBIH	:	Powder Bed And Inkjet Head
PolyJet	:	Polymer Jetting
PP	:	Plaster-Based 3D Printing
SAE	:	Standard Aerospace Equipment
SHS	:	Selective Heat Sintering
SIMP	:	Solid Isotropic Material With Penalization
SL	:	Sheet Lamination
SLA	:	Stereolithography Apparatus
SLS	:	Selective Laser Sintering
SO	:	Structural Optimization
TEI	:	Tusaş Engine Industry
TO	:	Topology Optimization
TRL	:	Technology Readiness Level
UC	:	Ultrasonic Consolidation
UV	:	Ultraviolet
VPP	:	Vat Photo Polymerization
3D	:	3 Dimensional
3DCP	:	3D Construction Printing

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# 1. INTRODUCTION

Topology optimization (TO) is an advanced technique that has recently gained significance in the context of additive manufacturing (AM). It employs mathematical algorithms to optimize the distribution and shape of material in a design to minimize weight while maintaining strength and other performance criteria. AM is a favorable fit for this method, as it allows for the production of intricate internal structures and complicated shapes that would be challenging to produce using conventional manufacturing techniques. The potential impact of TO is significant, as it can revolutionize product design and manufacturing by producing parts that are customized for specific applications and requirements. The analysis of loads and stresses on a part is crucial to TO as it determines the optimal shape and material distribution to meet the desired strength and stiffness goals while minimizing weight. This can result in parts that are more efficient, stronger, and lighter than those produced using conventional manufacturing techniques.

AM offers the necessary flexibility to actualize the intricate geometries and internal structures produced by topology optimization algorithms. With the ability to add material layer by layer, AM facilitates the creation of parts with precise geometries that are meticulously calibrated for optimal performance. This amalgamation of TO and AM could establish a novel manufacturing paradigm, where parts are specifically designed and optimized for additive manufacturing.

As the technology develops further and becomes more widely accessible, TO for AM could become a groundbreaking tool for designers and manufacturers. This could lead to a considerable enhancement in the performance and sustainability of products in several industries such as healthcare, automotive, aerospace, and construction, by producing parts that are more lightweight, robust, and efficient.

The objective of this thesis is to explore the effectiveness of TO in AM for aerospace applications through a case study analysis. The study seeks to uncover the benefits of utilizing TO in the design and production of brackets, including improved engine performance, reduced weight, and enhanced mountability. The research will focus on optimizing design parameters, such as build orientation, to enhance the strength, durability, and reliability of aerospace components while lowering manufacturing costs.

The case study will entail the development of a specific piston engine bracket using TO and AM, with emphasis on examining the impact of design modifications on the part's characteristics and performance. The investigation will evaluate several factors, such as the influence of optimization on the structural stability and mountability of the component, as well as the feasibility of upscaling the manufacturing process to fulfill industry demands.

Ultimately, this thesis aims to offer the implementation of TO in AM for the aerospace industry, with the objective of demonstrating the advantages of this approach in the design and production of aircraft components. The research will make a contribution to the larger knowledge base on advanced manufacturing techniques in the aerospace industry and the potential of TO to stimulate innovation in this field.

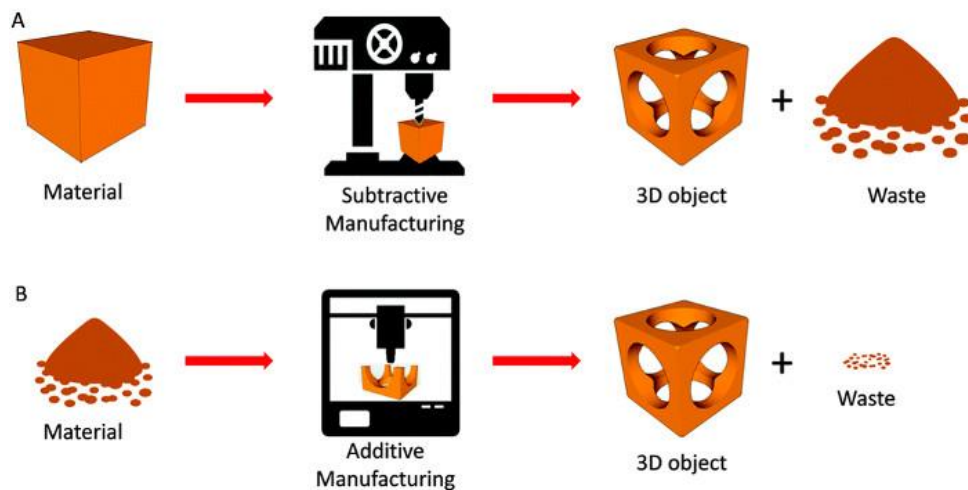


## 2. LITERATURE SURVEY

### 2.1 Additive Manufacturing

AM is a production technique that has gained widespread adoption. It involves creating 3D objects by adding material layer by layer, using various materials such as plastic, metal, concrete, and potentially even human tissue in the future. This technique, also known as rapid prototyping or free-form manufacturing, amalgamates materials often stacked on top of each other to build objects based on 3D model data. The ASTM has defined 'additive manufacturing' as a process that involves joining materials to create objects from 3D model data, typically layer upon layer, as opposed to subtractive methodologies like conventional machining [1].

Figure 2.1 shows a comparison between AM and subtractive manufacturing. In traditional manufacturing, a 3D object and waste material are produced when subtracting from a whole raw material. In additive manufacturing, the raw material is powder and is used as much as needed for the 3D object. This situation reduces the amount of waste.



**Figure 2.1: Subtractive manufacturing vs additive manufacturing [4]**

AM emerged in the 1980s as a result of increased military funding for exploring science and industrial technologies towards the end of the Cold War. Dr. Hideo Kodama utilized knowledge from 3D scanning and layering patterns from 3D topographical maps to develop a prototyping machine in the first quarter 1980s.

Stereolithography Apparatus (SLA) is invented in 1984 by Charles Hull and established the first 3D printing company in 1986. On the other hand Fused Deposition Modeling (FDM) technology is developed by Scott Crump, which he patented in 1989 and formed Stratasys INC.

Medical applications for 3D printing technology were not developed until 1999, when scientists were able to print synthetic scaffolds required for growing a human bladder. However, early studies demonstrated that 3D-printed organs were either non-functional or could only function for a limited time.

During the early 2000s, printing technology advanced significantly. The first commercially viable Selective Laser Sintering (SLS) machine was developed. Desktop FDM printing became accessible to the general public thanks to MakerBot, resulting in a surge of 3D printing enthusiasts.

AM has grown in popularity and continues to evolve. PolyJet technology is capable of jetting photopolymers onto the build plate and curing the material with UV light, generating high-resolution parts with detailed features that closely mimic the final resolution. The printer also creates a gel-like substance to serve as support material for intricate geometries, which can be readily removed once the build is complete.

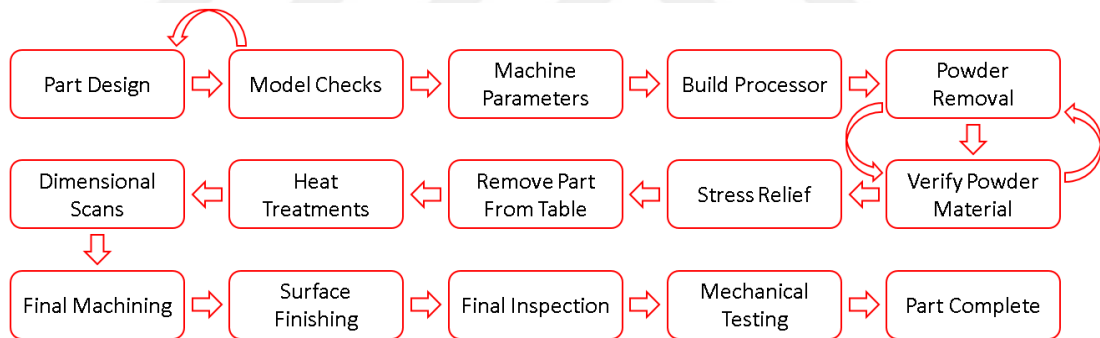
Compared to traditional manufacturing methods, AM generates minimal waste with buy-to-fly ratios ranging between 1-3 times. This not only decreases manufacturing costs but also simplifies recycling and reprocessing. AM also reduces lead times, particularly for aerospace alloys that necessitate extended lead times to create wrought starting stock material. AM has shifted from solely being used for rapid prototyping to final production, including for critical mission components.

AM provides a significant advantage in producing highly customized and complex parts in a single step, making it an ideal solution for prototyping. Designers can quickly iterate and refine their designs without the need for costly molds or tooling, which saves both time and cost. In certain cases, AM can even be used for low-volume production runs of specialized parts, reducing the need for expensive tooling and equipment. However, the process of AM is not as simple as it seems. While it reduces the production time and waste material, the pre-production steps are quite complex and require attention to detail. Thus, AM is being used in different

sectors like as aerospace, defense, construction, healthcare, automotive, and home decoration.

In the literature, examples in the field of aerospace have been given importance alongside the selected case study. The aerospace sector has made substantial use of additive manufacturing (AM) to make lightweight, high-performance parts, frequently with intricate geometries that are difficult to obtain using conventional production techniques. By reducing the weight of aircraft parts, the overall fuel consumption can be minimized, resulting in significant cost savings and environmental benefits. Additionally, the design flexibility provided by AM makes it possible to produce components with internal structures and forms that are optimized, enhancing their performance and a long lifespan.

The production process of AM consists of several steps, from the design phase to the ready-to-use state of the product. Figure 2.2 illustrate the steps involved in the production process. The AM process basically includes cad pre-process, data preparation, machine preparation, manufacturing, part removal and post-process steps.



**Figure 2.2: AM process steps illustration**

## 2.2 Categories of Additive Manufacturing

The international standard ISO/ASTM 52900 [9] provides a definition of AM, which consists of seven categories. Two of these categories, directed energy deposition (DED) and powder bed fusion (PBF), enable the production of metal components. Although other process categories also exist, they are not discussed in this thesis detail because they are still under development. AM processes such as DED and PBF are commonly used to produce high-quality metal parts for automotive, medical, and aeronautical industries.

**Table 2.1: The AM Process Categories by ASTM F42 [19]**

Process Types	Brief Description	Related Technology	Materials
<b>Powder Bed Fusion</b>	Thermal energy selectively fuses regions of a powder bed	Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)	Metals, Polymers
<b>Directed Energy Deposition</b>	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Laser metal deposition (LMD)	Metals
<b>Material Extrusion</b>	Material is selectively dispensed through a through nozzle or orifice	Fused deposition modelling (FDM)	Polymers
<b>Vat Photo Polymerization</b>	Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Stereo lithography(SLA), digital light processing (DLP)	Photopolymers
<b>Binder Jetting</b>	A liquid bonding agent is selectively deposited to join powder materials	Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)	Polymers, Foundry Sand, Metals
<b>Material Jetting</b>	Droplets of build material are selectively deposited	Multi-jet modelling (MJM)	Polymers, Waxes
<b>Sheet Lamination</b>	Sheets of material are bonded to form an object	Laminated object manufacturing(LOM), ultrasonic consolidation (UC)	Paper, Metals

Each type of AM technology has different strengths. These can be summarized as follows [9]:

- **PBF:** PBF is a highly accurate and precise metal 3D printing process that is generally used in aeronautical and medical industries to produce complex and high-performance parts with intricate geometries. PBF offers a extensive of design litness. The process is also capable of producing parts with high durability and strength, making it an ideal solution for applications that require good performance and reliability, such as aerospace and medical components.

- **DED:** DED is a metal 3D printing technology that is capable of producing large, complicated metal parts with high precision and accuracy. DED is often used in aerospace and automotive industries to produce complex components with intricate geometries, as well as for repairing and remanufacturing worn or damaged parts. This method is also maximally adaptable and allows for the use of a variety of materials, including alloys, metals, composites, making it a versatile solution for a variety of applications.
- **FDM:** FDM is known for its ability to manufacture large, low-cost geometries quickly. It is commonly used for creating custom parts and functional prototypes due to its ability to print in a variety of materials, including thermoplastics, and its ease of use.
- **VPP:** VPP is actually known as Stereolithography (SLA) and Digital Light Processing (DLP), both of which utilize photopolymer resins that are cured with UV light to create detailed parts with a smooth surface finish. These technologies are indeed ideal for creating parts that require high accuracy and precision, such as dental implants or jewelry.
- **BJ:** BJ is suitable for producing parts with high resolution and accuracy. Additionally, BJ can produce parts with a high degree of complexity, including internal cavities and undercuts. However, the parts produced by BJ are typically not as strong or dense as those produced by other AM technologies, making it more suitable for prototyping and low-volume production rather than high-stress applications.
- **MJ:** MJ is known for its high level of accuracy and precision. This technology is also capable of producing full-color parts, which is a unique advantage over other 3D printing technologies. Another strength of MJ is that it enables the use of multiple materials in a single part.
- **SL:** One of the strengths of SL is its high volumetric build rates. This means that it can produce parts relatively quickly, which is an advantage for production applications. Another advantage of SL is its ability to combine metal foils, including embedding components, into a 3D printed part. This allows for the design of geometries with unique combinations of materials and properties, which is useful for a wide range of applications.

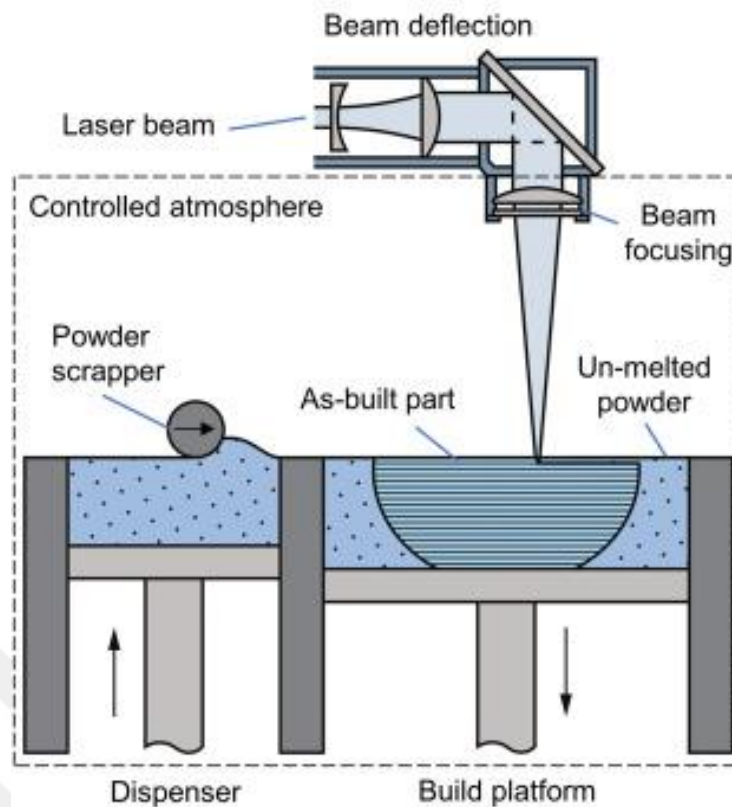
As they are relevant to the thesis topic and are frequently used in the aviation industry, PBF and DED methods are clarified in section 2.2.1 and section 2.2.2 detaily.

## **2.2.1 Powder Bed Fusion**

### **2.2.1.1 Laser Powder Bed Fusion**

L-PBF is a type of AM that utilizes high power lasers to melt and solidify layers of metal powder [24]. The process involves the selective melting and solidification of powder fed onto a platform, based on a CAD design. For the particular material and system being utilized, parameters like the laser scanning technique, thickness of layer, inert environment, and gas flow may be modified and optimized. The most used method for metal AM is L-PBF, which works with a variety of materials. It is somewhat expensive and is best suited for industries where high-value components and improved performance may lead to cost savings, such as aerospace, despite the fact that it can make completely dense components with great precision in a relatively short length of time.

Figure 2.3 shows schematically the working principles of the L-PBF method. Basically, there are laser beam, powder scrapper, moving powder dispenser and moving build platform. The powder scrapper spreads the fine powder layer on the platform. Then, in a controlled atmosphere, the programmed surfaces are heated via laser beam. When the operation on the relevant layer is completed, the platform moves downwards and a new layer of powder is laid with the powder scrapper. The operations are repeated until the part is manufactured.

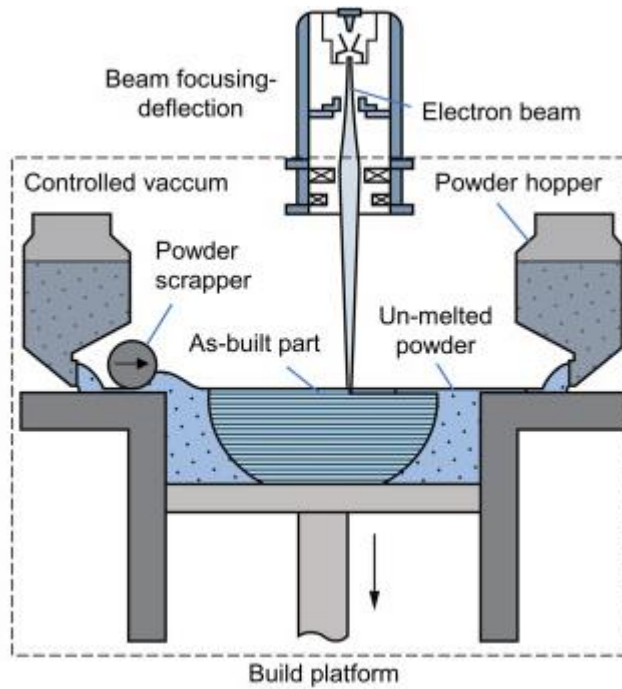


**Figure 2.3: Schematic illustration of the L-PBF's operating system [24]**

### 2.2.1.2 Electron Beam Powder Bed Fusion

A high-energy electron beam is used in the EB-PBF AM process to melt metal powder layer by layer, creating completely dense solid components [24]. The process occurs in a vacuum controlled atmosphere, which minimizes impurities and is especially useful for materials sensitive to oxygen. To reduce residual stresses, the system utilizes preheating by rapidly scanning the electron beam across the powder before melting a powder layer. The mechanical properties of components created via EB-PBF are comparable to those manufactured by traditional methods, demonstrating their suitability. The systems typically utilize larger feedstock powder sizes, resulting in rougher surfaces. Nevertheless, these systems are well-developed and provide relatively short build times due to the high power and rapid scanning of the electron beam.

Figure 2.4 shows schematically the working principles of the EB-PBF method. The main difference from the L-PBF method is the use of an electron beam instead of a laser beam and the vacuum controlled environment.



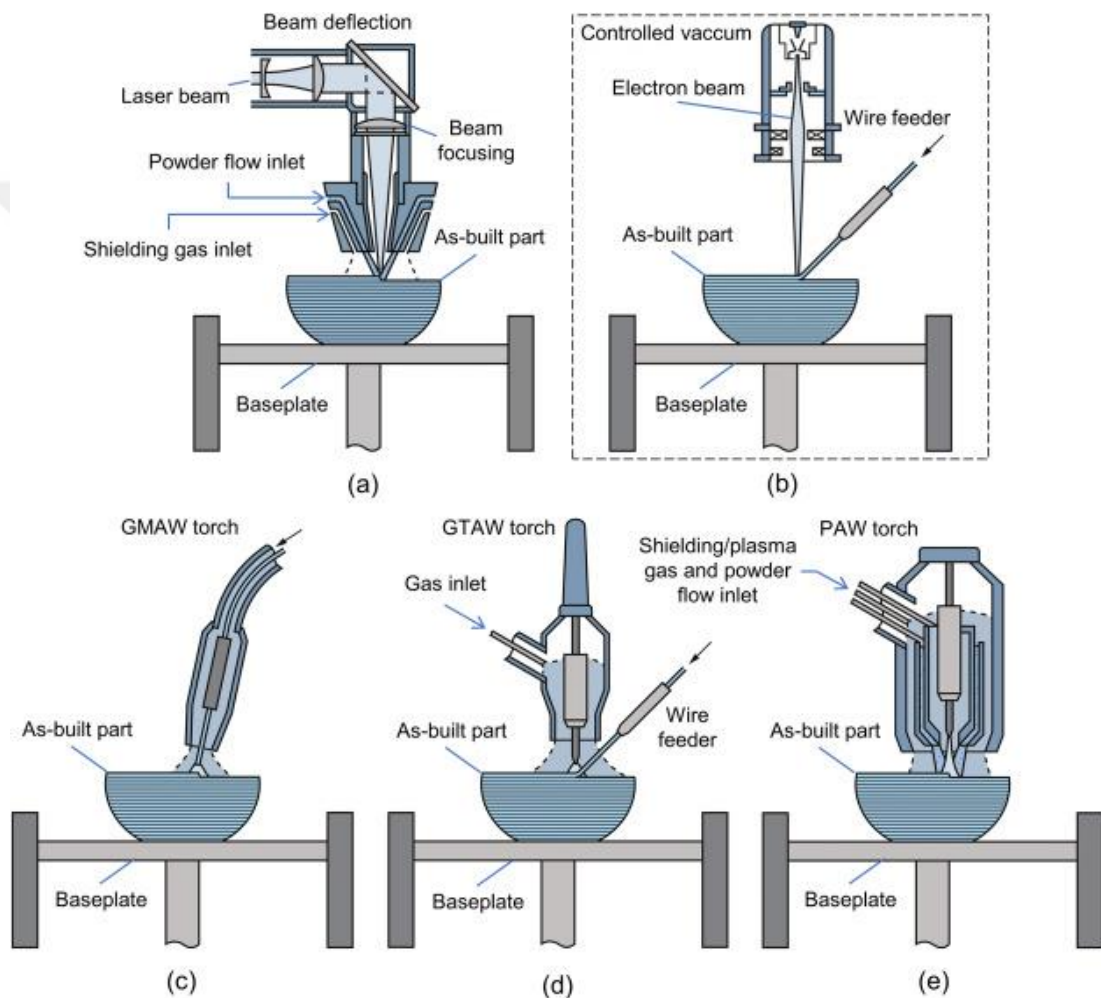
**Figure 2.4: Schematic illustration of the EB-PBF's operating system [24]**

### **2.2.2 Directed Energy Deposition**

In contrast to powder bed procedures, DED techniques deposit the stock material on-site utilizing wire or powder feedstock directly into the melt pool produced by an energy source like an electrical arc, laser, or electron beam [30]. DED permits the production of very big components since it provides geometrical freedom and is not constrained by build size. Turbine blades and other high-value existing parts are frequently repaired using DED equipment. However, compared to powder bed-based technologies [6, 25], DED has a lower resolution (minimum feature sizes of roughly 1 mm), making it more appropriate for bigger components with lower resolution [34] or places where post-processing machining operations can be carried out.

There are different forms of DED techniques that have varying advantages and disadvantages. Figure 2.5 shows schematically the working principles of the DED methods. It is mainly classified according to the energy source and whether it is in a vacuum-controlled environment. One of the most popular employs a laser as the energy source and powder as the feedstock is Laser Direct DED (LD-DED). The deposition head utilizes a local inert or fully purged chamber and is mounted to a robotic or gantry system. In LD-DED, the previous layer is linked with the powder

by blowing it into the melt pool. This results in a freeform structure. A different DED technique called laser wire DED (LW-DED) employs wire as the feedstock rather than powder, which has a high material efficiency but lower resolution. Other systems use wire with an electric arc or an electron beam as the energy source, such as AW-DED and Electron Beam DED (EB-DED). Each of them has a different feature resolution and deposition rate, which affects the heating and cooling speeds as well as the mechanical, thermophysical, and metallurgical properties [2, 11, 12, 33].



**Figure 2.5: Schematic illustration of the DED-based processes' operating system. (a) LD-DED, (b) EB-DED, (c) GMA-DED, (d) GTA-DED, (e) PA-DED**

[24]

## 2.3 Uses of Additive Manufacturing Technology

Many industries, including aeronautical, medical, and automotive, can benefit from AM's innovations, process improvements, and increased agility. AM is a flexible company that can create complicated or unique items. AM technology is used by manufacturers in a variety of ways to speed up production or enhance the quality of the finished product. Due to AM's adaptability, businesses may use 3D printers for a variety of tasks throughout the production cycle. Modern 3D printers combine robust resins, cutting-edge software, and cutting-edge hardware that are created for specialized purposes. In comparison to other production techniques like traditional manufacturing, additive manufacturing (AM) solutions also allow designers to make things with more intricate geometric designs.

The following are some AM applications:

**Prototyping:** AM is an excellent option for accelerated prototyping due to its speed, wide material selection, and design freedom. Companies can leverage 3D printers to produce both aesthetic and functional prototypes.

Designers can improve models at the aesthetic prototyping stage to assess design elements like shape, texture, ergonomics, and scale. Multiple prototype designs can be produced by a single 3D printer in a single batch, allowing designers to create a final model more quickly. Although aesthetic prototype does not call for the final production materials, it does give designers and marketing teams a glimpse of what the finished product will look like.

Additionally, businesses can use AM to build practical prototypes that test the operation and efficiency of various mechanical features. Designers can use functional prototypes the same way they would the finished product because they are made from materials suitable for manufacturing. Companies may conduct field tests early thanks to how simple it is to create practical prototypes, hastening the approval of the final product.

**Tooling:** In traditional manufacturing, tooling often limits production. However, AM can create tools such as jigs and fixtures that improve existing workflows. These devices enhance efficiency, enabling workers to repeatedly machine and accurately assemble products. With AM technology, making unique or

complex designs is simplified into one printing operation, streamlining the production process.

In besides tooling, AM can directly make surgical instruments or thermoform molds for dentistry purposes. Traditional thermoform molds need a lot of machining effort and hand labor to produce precise forms. All design work and revisions are done digitally when using 3D printing, which reduces the requirement for labor.

Moreover, AM can produce end-use parts on an industrial scale without requiring tooling, unlike traditional manufacturing methods such as injection molding. This advantage leads to faster production of new parts or products, with lower minimum order quantities and less design restrictions. The design flexibility of AM also enables companies to make design changes without incurring high costs.

**Full Production:** Full-scale production is possible with AM as it can produce end-use parts without the need for tooling, which is required in traditional manufacturing methods such as injection molding. This eliminates the time and cost associated with tooling, allowing for the rapid production of new parts or products. Moreover, there are fewer design restrictions and a lower minimum order quantity with AM compared to other manufacturing methods. Companies can also make design changes more easily and at a lower cost due to the design flexibility of AM.

Besides, AM eliminates the need for manual labor and simplifies the production process by allowing all design work and adjustments to be made digitally. The main industries where these methods are used are as follows sections.

## **2.4 Industries Benefiting from Additive Manufacturing**

### **2.4.1 Construction Industry**

The construction industry could be revolutionized by AM, or 3D printing, which can create complex geometries and structures that are difficult, if not impossible, to achieve with traditional construction methods. This technology can also reduce waste and lead to cost savings. Several AM techniques, such as concrete printing, PBF, and extrusion, can be used in construction, each with its own advantages and limitations. Concrete printing, in particular, has great potential in construction, allowing for the creation of customized structures that can be built faster and more efficiently than with traditional methods, while reducing waste and the environmental impact of construction.

AM in construction offers several benefits, such as the ability to create custom, complex structures quickly and efficiently, while reducing waste and the environmental impact of construction. Additionally, it can save time and money by minimizing the need for manual labor and by allowing the creation of prefabricated components that can be assembled on-site. However, despite these advantages, the technology is still in its early stages and faces various technical and regulatory challenges before it can be widely adopted. Nevertheless, as more companies experiment with additive manufacturing in construction and the technology continues to improve, it is likely to become an increasingly important part of the construction industry in the coming years. With the advancement of technology in the construction sector, settlement areas can be created thanks to additive manufacturing, before the establishment of colonies on Mars or the other planets of the solar system, which is expected to be visited in the near future.

AM systems suitable for concrete extrusion printing can be categorized based on various factors, such as object size, layer thickness, printing conditions, assembly approach, use of support structures. The most common type of AM system for this purpose is the 3-axis printing device, which usually produces layers that are a few centimeters thick. However, there has been limited exploration of component assembly and support structures. Despite this, several successful projects have been completed using these AM systems [26].

For instance, Loughborough University's 3DCP concept was used to create a curved bench with structured surfaces and individually shaped voids to reduce weight and enable post-reinforcement placement. The printing process took approximately 42 hours [26].

XtreeE printed a complex-shaped wall-element measuring  $1.36 \times 1.50 \times 0.17 \text{ m}^3$  using a 6-axis robot arm to optimize thermal insulation. The printing process took around 12 hours [35].

WinSun used a process to print components for a 250 m<sup>2</sup> single-floored office building for the Dubai Future Foundation. The printing process took 17 days, and the parts were assembled in Dubai within 2 days [26].

Eindhoven University of Technology constructed a 6.5 m span bicycle bridge with a width of 3.5 m using 3DCP (Figure 2.6). The superstructure of the bridge consisted of printed elements interconnected by subsequently installed tendons, with

some layers containing embedded reinforcement cables. All elements were printed within 48 hours [26].



**Figure 2.6: Example of 3D Concrete Printing [36]**

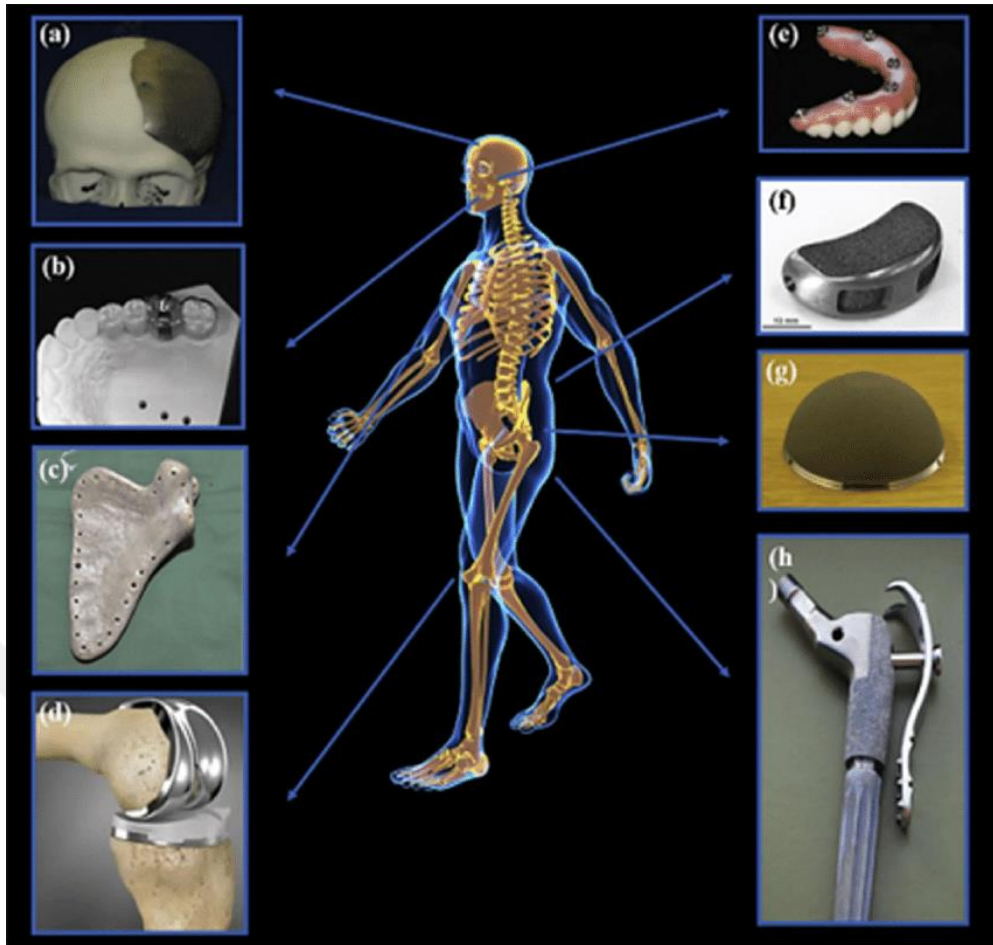
## **2.4.2 Medical and Dental Industries**

The health sector has also experienced significant advancements due to AM. This technology has transformed the production of medical and dental devices, implants, prostheses, and models, offering unparalleled levels of precision, customization, and affordability.

### **Medical Industry:**

AM has emerged as a valuable tool in the development of personalized implants, prosthetics, and surgical instruments. For instance, complex titanium implants and prostheses can be manufactured with porous structures that enhance tissue integration and bone growth. Additionally, AM can produce patient-specific surgical guides that enable more accurate and efficient surgeries, reducing the risk of complications and improving patient outcomes.

Furthermore, the production of bioprinted tissues and organs is a groundbreaking application of AM in regenerative medicine (Figure 2.7). By utilizing a patient's own cells, bioprinting can produce tissues and organs that are biologically compatible, decreasing the risk of rejection and increasing the success rate of transplants [32].



**Figure 2.7: Image of the biomedical implant fabricated through AM technique [32]**

The global market for AM in healthcare was valued at USD 1.6 billion in 2021 and is expected to grow at a compound annual growth rate of 22.6% from 2022 to 2030 [37]. This growth is driven by the rising demand for personalized medical products, including implants, and the development of advanced technologies capable of producing both simple and complex designs. The ability to create intricate and tailored medical components such as organs, tissues, dental prosthetics, and orthopedic and cranial implants has led to AM being hailed as the next industrial revolution in manufacturing [37].

**Dental Industry:**

The dental industry has seen a significant transformation due to the implementation of AM technology. Dental labs can now create highly precise and personalized dental models, implants, and prostheses in a fraction of the time it used to take. With the use of AM, dental professionals can design and produce crowns,

bridges, and orthodontic devices with intricate, patient-specific details that fit better and look more natural.

In addition, AM has enabled the production of clear aligners that are tailor-made for each patient, offering a more comfortable and effective alternative to traditional braces. 3D printing has also made it possible to manufacture surgical guides for dental implant placement, reducing the risk of complications and increasing the precision of the procedure [32].

### **2.4.3 Automotive Industry**

The past decade has witnessed significant changes in the automotive industry due to the adoption of AM technology. This state-of-the-art technology enables the production of intricate and complex parts with high precision and ease. The ability to manufacture parts in a shorter time frame than traditional methods is one of the primary reasons why additive manufacturing is fast becoming a game-changer in the automotive sector.

According to industry projections, the automotive industry is expected to use approximately \$530 million worth of 3D printing materials in 2021, with an estimated revenue potential of up to \$9 billion by 2029 [38].

One significant advantage of AM for the automotive industry is the speed at which new designs can be prototyped. This allows engineers to create and test new components quickly and efficiently, thereby reducing the overall cost and time required to bring new products to market. Furthermore, 3D printing allows for the creation of complicated parts and internal structures that would otherwise be impossible to produce using conventional manufacturing techniques.

Another key benefit of AM in the automotive industry is the ability to create lightweight parts. Weight reduction is critical in the automotive industry, as it directly impacts fuel efficiency and performance. By using 3D printing to produce lightweight parts, automakers can improve fuel economy and reduce emissions, all while maintaining or improving performance.

Furthermore, AM technology can be used to produce customized and personalized parts, such as interior components and exterior trim pieces. This allows automakers to cater to individual customer preferences and create unique, high-quality vehicles.

There are a few challenges associated with using AM in the automotive industry, however. One of the most significant is the cost of the technology and materials. While the cost of 3D printing has come down in recent years, it is still more expensive than traditional manufacturing methods for large-scale production runs. Additionally, the materials used in 3D printing are still somewhat limited, which means that not all parts can be produced using this technology.

Despite these challenges, AM is poised to revolutionize the automotive industry in the coming years. With its ability to reduce time-to-market, create complex parts, and improve performance and fuel efficiency, this technology is sure to be a game-changer in the automotive world [31]. Figure 2.8 shows current and future applications of AM in the automotive technology.



**Figure 2.8: Current and future implementation of AM on automotive [31]**

### 2.4.4 Manufacturing Industry

AM has emerged as a game-changer for the manufacturing industry, offering unprecedented precision, speed, and cost-effectiveness in designing and producing complex parts. Unlike traditional manufacturing methods such as subtractive manufacturing, which involve cutting or drilling materials to shape them, AM involves building three-dimensional objects layer by layer from digital models. This eliminates the need for tooling and molds, reducing production time and costs, making it ideal for small-scale manufacturing.

One of the most significant advantages of AM is its ability to produce complex geometries that were previously impossible or impractical with traditional methods. For instance, AM can create intricate lattice structures that are lightweight, strong,

and resilient, making them suitable for aeronautical, automotive, and medical implementations. Moreover, AM enables rapid prototyping, allowing designers to iterate and refine their designs quickly, reducing the time and cost of developing new products. This capability helps manufacturers bring products to market faster and more efficiently, contributing to the continued growth of AM in the manufacturing industry.

Additionally, AM contributes to sustainable manufacturing practices by reducing waste in the manufacturing process. Unlike traditional methods that generate significant amounts of scrap material, AM only uses the material required to produce the part, lowering the overall carbon footprint of the manufacturing process.

However, there are still challenges associated with AM, such as limited material options, part size, and surface finish. Despite significant progress in recent years, the technology still struggles to produce large parts with high precision and surface finish.

In conclusion, AM is revolutionizing the manufacturing industry, offering new design and production possibilities, faster time-to-market, and sustainable manufacturing practices. Despite challenges, AM is expected to become a dominant force in the manufacturing industry, enabling manufacturers to produce complex, innovative, and environmentally-friendly products.

#### **2.4.5 Aerospace and Defense Industry**

The aerospace industry encompasses diverse sectors such as commercial and military aircraft, space launch and in-space systems, missiles, satellites, and general aviation. The manufacturing process in this industry requires balancing multiple technical and economic objectives, including functional performance, lead time reduction, lightweighting, complexity, cost management, and sustainment. These objectives are interdependent and must be carefully considered to achieve an optimal design solution. The relative importance of these objectives varies depending on the specific aerospace application.

Safety-critical components in the aerospace industry must operate with high functional performance in their intended environment, despite being produced in small volumes with a relatively inflexible delivery schedule. Therefore, reducing lead time is crucial for rapid product certification and maintaining design flexibility for high-value components.

Achieving lightweight structures is a crucial consideration for both technical and economic performance in aerospace. By reducing the mass of systems, benefits such as lower fuel costs, reduced emissions, increased payloads, and extended range can be achieved. However, economic factors such as cost management must also be taken into account, as there is a specific financial resource available for each design objective. Objectives like lightweighting and lead time reduction can increase the allowable system cost, and cost management applies to all aspects of component use, including certification and maintenance.

However, metal AM faces a significant challenge in the aerospace industry, specifically regarding certification. Regulatory bodies require confidence that AM systems are thoroughly understood, can be designed and inspected repeatedly, and meet reliability and safety expectations. Certification requirements vary according to the criticality of the proposed AM system. To achieve practical certification, connections with existing standards for traditional manufacturing and emerging standards for AM processes are required [20].

The aerospace industry is constantly striving to improve efficiency and meet commercial or mission requirements by utilizing high-performance materials and increasingly complex designs, while also reducing costs and lead times. While traditional manufacturing systems have been developed to meet these objectives, AM is transforming design and manufacturing processes. This digital transformation is expected to drive the market size of AM in aerospace to \$3.187 billion by 2025, with an average annual growth rate of 20.24% [20]. Over the past decade, research into AM has expanded rapidly, with scholarly literature, technical reports, and articles from commercial aerospace suppliers providing valuable insights.

AM presents several challenges in aerospace manufacturing, including limited material options, uncertain material properties, specific design constraints, post-processing requirements, waste generation, increased design skills requirements, and the need for strict quality control and certification. Although accessibility to AM machines is growing, the technology is not yet as widely available as traditional manufacturing methods, and the supply chain requires further development. Post-processing can be difficult, requiring specialized thermal treatments, part cleanliness, and surface enhancements to improve rough surfaces.

Furthermore, AM in aerospace must comply with strict quality controls such as Quality Systems - Aerospace SAE AS9100 and Standard for Additively Manufactured Spaceflight Hardware MSFC-STD-3716, NASA Standard 6030, which are complicated by the complexity of the AM processes and their many potential influences on component quality. While several international standards are being developed to address these issues, material performance and required controls may differ from those of traditional manufacturing. Nevertheless, with appropriate quality controls and optimization procedures, the challenges associated with AM in aerospace can be mitigated or minimized.

## **2.5 Advantages of AM for Aerospace and Defense Industry**

In the aerospace sector, the idea of lightweighting design has received a lot of attention due to its potential to lower fuel costs by lowering the mass of airplanes and spacecraft. In order to minimize emissions and reach the International Civil Aviation Organization's aim of a 50% reduction in aviation emissions by 2050, there is now a rising push to improve the energy efficiency of airplanes. Techniques for mass reduction are some of the best ways to reach this goal. For instance, if the mass of a Boeing 787 were to be decreased by 20%, this may lead to improvements in acceleration and other performance factors as well as a 10-12% increase in fuel economy [49].

The mass of components in airplanes and spacecraft has been decreased because to the adoption of additive manufacturing techniques, which have also been proved to lower prices and lead times. While mass reduction is a potential advantage, lead time reduction—particularly for complicated systems that take months or years of traditional fabrication time—is now the main impetus for AM in aerospace. For example, the A320 nacelle hinge bracket was created utilizing AM techniques, which resulted in a 64% mass reduction over the original design. About half of this mass advantage was achieved by using Ti-6Al-4V rather than the original HC101 steel. For the duration of the nacelle hinges' operating lifespan, this mass reduction in conjunction with further design improvements enabled a 40% decrease in CO2 emissions [29].

Rapid prototyping, lightweighting structural components, and the creation of intricate instrumentation devices are just a few of the advantages that AM technology

provides for the aerospace sector, according to [27]. The most recent developments in AM technology have made it possible to produce even the most technically difficult components, making them perfect for low-quantity space applications that need considerable cost and mass reductions to accelerate space exploration. Every gram saved translates into more payload capacity and cheaper launch costs because space missions may cost more than €20,000 per kilogram [39].

Along with lightweighting, AM also provides part consolidation, which has several advantages across a variety of sectors and is a key advantage in aircraft applications. Ariane 6 rocket injector head, which was produced using AM and reduced the weight of the head compared to conventional manufacturing techniques by combining 248 separate components into a single piece [40]. Since 2013, NASA has also proven many AM applications to rocket engine injectors, leading to notable reductions in part count and lead time. For instance, one of the samples demonstrates a decrease from 115 parts to 2 parts. The injector was tested in full operating settings and demonstrated performance comparable to those of injectors made conventionally [41, 42].

Part consolidation, which minimizes the amount of parts needed and does away with the requirement for assembly processes, joining techniques, and equipment, is a significant advantage of AM in aerospace applications. For instance, compared to conventional production techniques, Pratt & Whitney's stator blades showed a 15-month lead time reduction and a 50% reduction in blade mass [43].

Additionally, Component consolidation also minimizes the amount of parts that need certification and the related paperwork, while also lowering manufacturing process risks. Further lowering the need for tooling and assembly, AM also provides design flexibility by potentially enabling the production of many components in a single build process. Due to their intricate internal structures and designs, heat transfer device applications are especially well suited for AM. The part count, lead time, lightweighting, cost, and performance of the heat transfer devices made via AM have all significantly improved.

The Cellcore AM rocket engine design is a good example of how sophisticated, complicated, high-performance components and structures benefit from AM processes. Since components may be manufactured on-demand from a digital library, AM also does away with the need for huge storage facilities and

cataloging of components, including older components that are no longer available [13].

NASA has made heat exchangers like combustion chambers and channel-cooled nozzles for liquid rocket engines using AM technology. GRCop-42, C18150, Inconel 718, and bimetallic copper-superalloy structures are a few examples of copper alloys that have been used in a variety of applications. 400 hot-fire starts and more than 30,000 seconds have been spent on these buildings. The use of channel-cooled nozzles built of alloys such as JBK-75, NASA HR-1, Inconel 625, Haynes 230, and bimetallic structures has also been proven by NASA. Over 11,000 seconds and more than 250 hotfire tests have been performed on these parts [5].

As high-value aerospace components, such as impellers, turbine blades, and airfoils, are frequently exposed to severe conditions, using AM methods for their repair offers a considerable advantage. The conventional technique of repair entailed welding operations, which might lead to the geometric deformation of the restored components and the generation of residual stress. When used effectively, AM methods may fulfill all structural design margins and operating requirements and provide advantages such as requiring less heat input during the repair process. The use of AM for these components has shown to significantly reduce costs and delivery times while still delivering hardware that meets performance standards [17, 44].

Hybrid manufacturing is a term that describes the blending of AM with conventional production techniques. The AGENT-3D\_IMProVe project, which used a hybrid process chain incorporating DED with wire filler material and traditional machining, is one example of this. In this project, the wire filler material was made of the nickel-based alloy Inconel 718. The usage of bimetallic structures by Virgin Orbit and NASA for the creation of combustion chambers is just one of many such instances of hybrid manufacturing that have been documented in the aerospace sector [7].

Additionally, GE Aviation has shipped the 100,000th fuel nozzle tip created using AM technology, marking a significant milestone. This accomplishment is significant for the business and the AM sector as a whole. The factory was the first to use AM in mass production of aviation engine parts in 2015. The gasoline nozzle tips are intended to be used with LEAP engines, which CFM International created and have been in use since 2016 [45].



**Figure 2.9: The first mass manufactured AM component for the aircraft segment, fuel nozzle [45]**

## 2.6 Structural Optimization

Structural optimization (SO) is the process of designing and optimizing structures to meet specific performance criteria while minimizing the use of material and resources. The goal of structural optimization is to create a structure that is efficient, safe, reliable, and cost-effective.

The optimization process involves using mathematical and computational techniques to analyze the behavior of a structure under various loads and conditions. This includes determining the stresses and strains within the structure, identifying potential failure modes, and exploring different design options to find the most effective solution.

Overall, SO is a critical field of engineering that can lead to significant improvements in the performance, safety, efficiency, and sustainability of structures. It is used in a wide range of applications, including aerospace, automotive, civil engineering, and many others.

There are some terminology that should be taken into account throughout an optimization process, such as [18]:

**Objective Function (f):** By returning a number that represents the design's current condition, the objective function rates designs. You may measure weights, stress, displacements, or cost with the objective function.

**Design variable (x):** The parameters that are changed in the issue formulation in order to fulfill the objective function are referred to as design variables. This

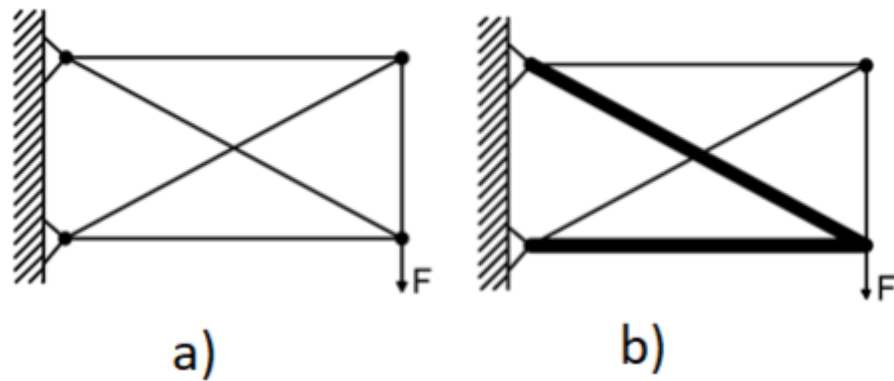
description can describe a wide variety of factors, including geometry or materials, and can be simple or complex.

State Variable ( $y$ ): A function that illustrates how a certain structure responds. Displacements, stress, strain, or force are possible responses.

Numerous variables and objective functions can be defined for the optimization process in order for it to achieve that goal. These characteristics could include things like reducing weight, increasing stiffness, or decreasing buckling length. To control the outcome of the aforementioned optimization process, constraints are, nevertheless, crucial. For instance, if there is no restriction on the amount of material, the structure may be made indefinitely stiff, with no upper limit on its weight or any other property. Therefore, one of these variables must be changed while utilizing the other variables as constraints in order to properly define an optimization problem [18].

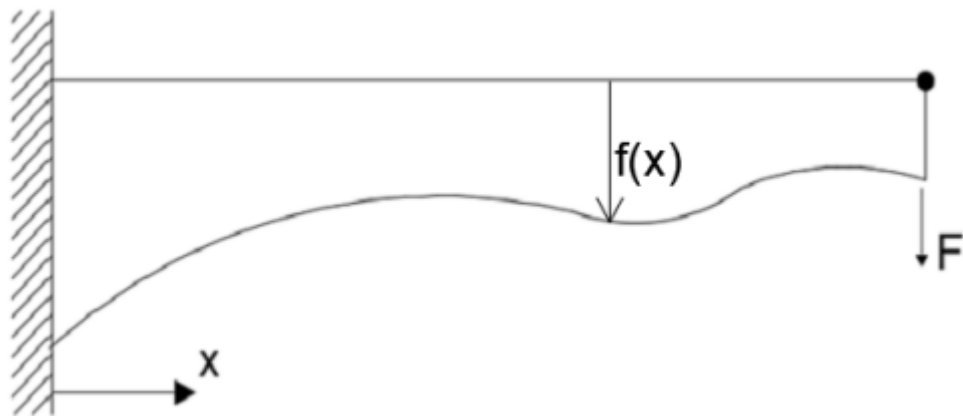
There are many different kinds of optimization techniques, including the iterative-intuitive approach and the mathematical design method. In contrast to the intuitive random search approach, which takes longer to find a solution, the mathematical optimization method's searching algorithm is directed by a set of mathematical formulations. However, in order to effectively apply mathematically based design challenges, a number of requirements must be met.

Size, shape, and topology optimization are three different categories of structure optimization. The geometry of the structure, as well as the loading and supporting conditions, must be predetermined prior to the optimization process in order to perform size optimization. The goal is to optimize the size of the members in the structural profile in order to arrive at the most cost-effective solution, or to fulfill the objective function. As an example Figure 2.10 displays a truss construction size optimization problem.



**Figure 2.10: Layout of a structure before its size is optimized (a), Layout of a structure after its size is optimized (b) [18]**

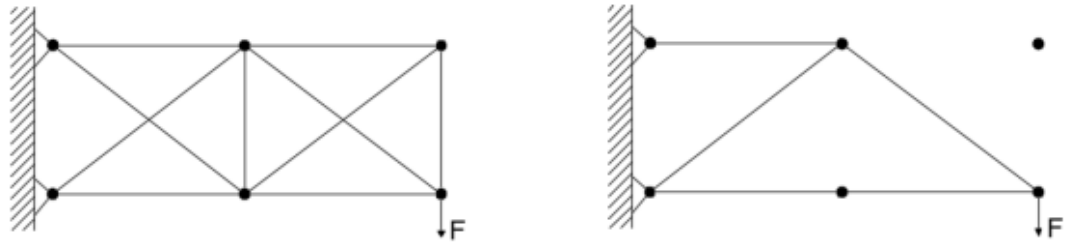
The size of the member and the structural system are not issues in form optimization. The shape issue is specified on a domain that is now the design variable, hence the objective is to determine this domain's ideal form. Shape optimization does not create new boundaries, altering the structure's connectedness. The domain is the design variable in a form optimization issue. As an example Figure 2.11 depicts a two-dimensional form optimization problem, finding the function  $f(x)$ , describing the shape of the structure.



**Figure 2.11: Shape optimization problem [18]**

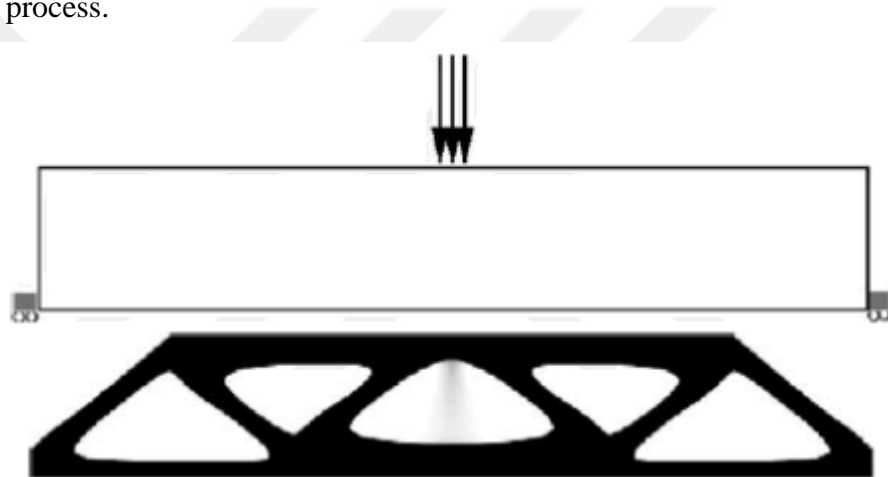
The third kind of structural optimization is topology optimization, which is the broadest kind. It is accomplished in a discrete situation, such as for a truss, by using the cross-sectional areas of the truss members as design variables and then allowing these variables to assume the value zero, which indicates that the truss's bars are eliminated. Solid structure topology optimization entails figuring out factors including the quantity, position, and geometry of holes as well as the domain's

connectedness [3]. In Figure 2.12, the TO procedure for a truss is illustrated clearly, with certain members eliminated by setting the cross sectional areas to zero.



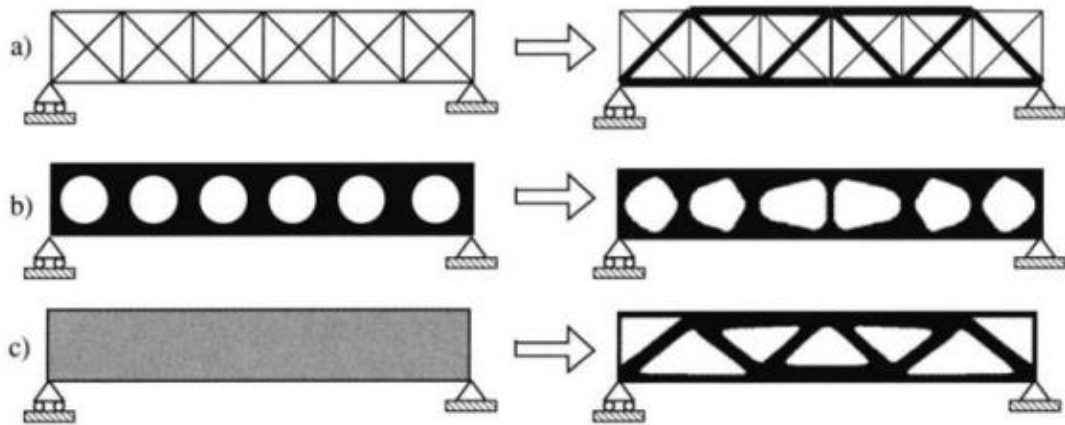
**Figure 2.12: TO of a truss [3]**

On the other hand, Figure 2.13 depicts a different sort of TO in which the domain is determined, but the structure's shape is developed throughout the optimization process.



**Figure 2.13: TO with volume fraction 50% [3]**

Figure 2.13, which compares the three forms of SO previously described, includes TO, shape optimization, and truss structure sizing optimization. The original issues are displayed on the left, while the ideal remedies are displayed on the right.



**Figure 2.14: Difference between various types of SO ((a) Size optimization, (b) Shape optimization, (c) Topology optimization) [18]**

### 2.6.1 Topology Optimization

TO is an optimization method that involves finding the optimal material distribution within a given design space while adhering to pre-determined restrictions such as loads and boundary conditions. The production, combination, and division of internal features like voids and solids within a part is possible with TO, in contrast to size or shape optimization. This flexibility in design allows for improved structural performance compared to size or shape optimization [15].

TO is particularly useful for AM technology due to its freedom of design capabilities [16]. The outputs from topology optimization are often used as inputs for subsequent size or shape optimization problems. However, the calculation time for TO can be lengthy as structural finite element analyses are conducted throughout each iteration until the final optimization result is reached. Typically, a TO model is stressed completely across its geometry based on pre-defined loading conditions [8]. The widely accepted density-based topology optimization technique is commonly known as the Solid Isotropic Material with Penalization (SIMP) method. In fact, many topology optimization software are developed based on this approach [8].

In the SIMP method, the initial geometry of the part is divided into volume elements, and the density of each volume element is considered as a design variable. The density values range between 0 and 1, where 0 represents voids and 1 represents fully solid material, and intermediate values represent porous material. The objective of the optimization problem is to determine the optimum density distribution within

the design space, while satisfying the pre-defined constraints such as loads and boundary conditions [8].

During each iteration of the optimization cycle, the density distribution is updated based on the results of finite element analysis (FEA), which is used to evaluate the structural performance. The stiffness penalty method is used to penalize the intermediate density values and to obtain the final solution, which is either fully solid or voids [8].

TO is an effective method for optimizing material distribution within a pre-defined design domain by adjusting the pseudo-density of variables [3]. To achieve better results, the design domain is typically larger than the base model in which external forces and boundary conditions are defined. The goal is to determine the lowest or maximum distribution while making sure that the restrictions are satisfied. Depending on the issue formulation, the state variable may include numerous variables. If the global compliance is the state variable, setting a maximum volume or mass fraction as a restriction is necessary to maximize stiffness. In addition, manufacturing restrictions may be applied to enhance the TO solution and provide designers with more useful design alternatives.

TO results are generally interpreted in terms of density fields, which can represent high stiffness domains or low stiffness domains. Figure 2.1 illustrates the three steps of TO, which include problem definition, initial TO results, and redesigned optimization that is adapted based on the manufacturing technology [28].



**Figure 2.15: TO from problem definition to structural design proposal [28]**

To solve a topology optimization problem, it is necessary to define the objective function and constraints. A typical formulation for a TO problem is as follows:

$$\begin{aligned}
 &\text{Minimize(or Maximize)} \quad f(\rho) \\
 &\text{Subject to} \quad \int_{\Omega} \rho dv \leq \bar{V} \\
 &\quad \quad \quad \rho(v)=0 \text{ or } 1, \forall v \in \Omega
 \end{aligned} \tag{2.1}$$

The objective function for topology optimization is represented by  $f(\rho)$ , where  $\rho$  is the density distribution within the design domain  $V$ . However, solving equation (2.1) directly is not feasible, and numerical methods must be employed. Typically, the  $\Omega$  domain is discretized into  $N$  finite elements, and the design variables are represented by  $\rho$ . The material distribution is then defined using the design variable vector  $\rho$ . The updated formulation can be observed in equation (2.2), where  $v_i$  represents the volume of the  $i$ th element.

$$\begin{aligned}
& \text{Minimize (or Maximize)} \quad f(\rho) \\
& \text{Subject to} \quad \sum_i^N \rho_i v_i \leq \bar{V} \\
& \rho(v) = 0 \text{ or } 1, i=1, \dots, N
\end{aligned} \tag{2.2}$$

While equation (2.2) provides a simplified version of equation (2.1), additional numerical methods are necessary to discretize topology optimization problems.

## 2.6.2 Topology Optimization for Additive Manufacturing

One of the main advantages of AM is that it enables the production of complex geometries that are difficult or impossible to produce using traditional manufacturing methods. This is because AM builds parts layer by layer, allowing for the creation of highly detailed and intricate geometries that would be difficult to achieve with subtractive manufacturing techniques like machining. Additionally, AM has the potential to reduce material waste and manufacturing costs, as it only uses the material that is required to build the part.

TO, on the other hand, is a design optimization technique that can be used to optimize the shape and distribution of material within a given design space to achieve a desired set of performance goals. TO can be used to minimize the weight of a part while maintaining its structural integrity, or to maximize its stiffness while minimizing its mass. By optimizing the shape and distribution of material within a given design space, TO can help to reduce material waste and manufacturing costs, while also improving the performance of the part.

When combined, AM and TO can provide a powerful set of tools for designing and manufacturing highly optimized, complex parts. One of the key benefits of combining AM and TO is that it enables the creation of highly optimized, lightweight structures. By using TO to optimize the shape and distribution of material within a given design space, designers can create parts that are highly optimized for their intended use. This can result in parts that are significantly lighter than those produced using traditional manufacturing methods, which can be important in applications where weight is a critical factor, such as aerospace or automotive applications.

Another benefit of combining AM and TO is that it enables the creation of multi-scale/multi-hierarchical structures. By using TO to optimize the shape and distribution of material within a given design space, engineers can create parts with highly complex internal structures that are optimized for their intended use. AM can then be used to manufacture these parts with the required level of detail and complexity, allowing for the creation of parts with highly optimized internal structures that would be difficult or impossible to produce using traditional manufacturing methods.

In order to take full advantage of the benefits of combining AM and TO, it is important to integrate AM design constraints into the TO process. This can help to ensure that the parts produced using AM are highly optimized for their intended use, while also taking into account the limitations of the AM process. For example, engineers can use TO to optimize the shape and distribution of material within a given design space, while also taking into account the need for support structures during the AM process [29].



**Figure 2.156: : Case study of a topology-optimized bracket [29]**

In conclusion, AM and TO are a perfect couple for designing and manufacturing highly optimized, complex parts. By combining these two advanced manufacturing technologies, designers and engineers can create parts that are highly optimized for their intended use, while also taking advantage of the benefits of AM, such as the ability to create complex geometries and reduce material waste.

### 2.6.3 Generative Design

TO and Generative Design (GD) are both computational design approaches that aim to create optimized parts or structures, but they differ in their focus and approach.

TO is a design optimization technique that seeks to find the optimal material distribution within a given design space to achieve a set of performance goals, such as minimizing weight while maintaining structural integrity. The optimization process typically involves iteratively removing or adding material to the design space, based on the predicted performance of the structure, until an optimal material distribution is achieved. The resulting design is typically represented as a mesh with varying material densities, which can then be further refined to create a final CAD model.

GD, on the other hand, is a design approach that uses algorithms and computational power to generate multiple design options based on a set of user-defined constraints and performance criteria. GD algorithms explore a range of possible design options, often using machine learning or artificial intelligence techniques, to create a set of optimized design solutions. The resulting designs are typically generated as CAD models that can be further refined or modified based on the user's preferences. While both approaches aim to create optimized designs, the main difference between TO and GD lies in their focus and approach. TO is primarily concerned with finding the optimal material distribution within a given design space, while GD is more focused on exploring a wide range of design options based on user-defined criteria.

Another key difference between TO and GD is the level of human input required. TO is typically driven by an engineer or designer who defines the design space and performance criteria, and makes decisions on how to refine the resulting optimized designs. Therefore, more inputs are required for TO. GD, on the other hand, is often more automated, with the algorithms generating multiple design options that are then evaluated by the user, who selects the best design for further refinement.

In summary, while both TO and GD are powerful design tools, they differ in their focus and approach. In this thesis, topology optimization will be used as a SO method and GD method will not be used.

## **3. CASE STUDY AND METODOLOGY**

### **3.1 Case Study**

#### **3.1.1 Applications of AM to Brackets in the Aerospace Industry**

Complex designs of load-bearing brackets for AM can occasionally have strange, almost organic-looking shapes and exhibit extraordinary strength-to-mass ratio properties. These designs can be effectively executed, but in order to fully take use of this technology, it is essential to have a thorough grasp of the entire load distribution and operating circumstances. Within the constraints of the particular AM technique, metal AM enables the fabrication of finely designed components utilizing a variety of materials and design strategies [14]. Production of brackets, structures, and frames uses TO and AM often in the aerospace sector. Until recently, producing lightweight organic structures required using conventional techniques, which had substantial limits such casting orientations, symmetry specifications, size restrictions, and tool path restrictions. In comparison to conventional manufacturing techniques, AM enables greater design complexity, which can be fully exploited through TO to further reduce the weight of components in aerospace applications [49, 50].

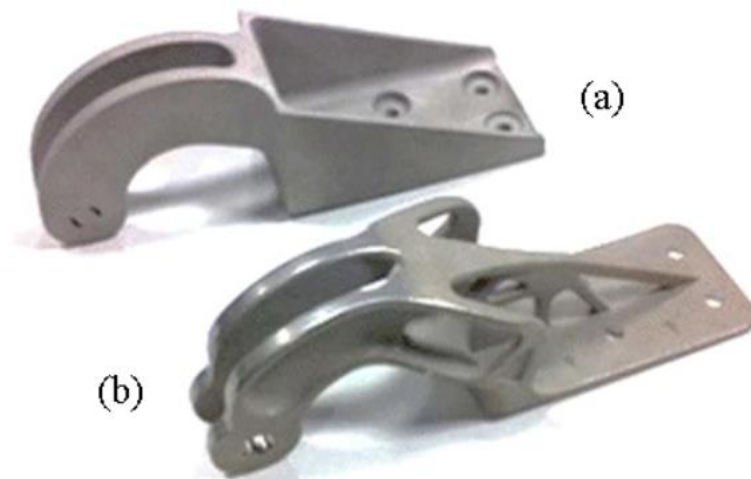
TO and metal AM technologies' progress has generated an explosion of new projects that aim to reduce component weight by combining TO and AM while avoiding the limitations of conventional production. Recent aerospace applications have had great success using a mix of TO and AM approaches [49, 50]. The A350 cabin bracket connection, one of the first structural components created utilizing TO and AM without the usual production limitations, is an early illustration of this strategy. In order to create the bracket from Ti-6Al-4V in 2014, Airbus used TO and AM processes, notably laser powder bed fusion (L-PBF), as shown in Figure 3.1 [10, 22, 23].



**Figure 3.1: Topology optimized and additive manufactured Airbus A350 XWB cabin bracket [10, 22, 23]**

The Norwegian business Norsk Titanium achieved a critical milestone in 2017 when it became the first to acquire authorization from the Federal Aviation Administration (FAA) to produce AM components using DED techniques that would be subject to in-flight stress loading [46]. These were the first structural AM components utilized in the Boeing 787 Dreamliner and were made of Ti-6Al-4V. The manufacturing and installation of a titanium vital support bracket for the A350 XWB then started that same year at Airbus. The airplane pylon, which connects the wings to the engine, has this AM-produced component as an essential component [47].

The Airbus A320 nacelle hinge bracket was the subject of a joint research initiative by EOS and Airbus Group Innovations, as shown in Figure [29]. This study set out to produce the component utilizing Ti-6Al-4V material and L-PBF methods in order to swap out the present hinge brackets on the engine inspection nacelles. The main objectives were to reduce mass and expense in comparison to the existing designs [29]. When compared to traditional casting procedures, the study showed that using L-PBF AM techniques gave important advantages in terms of bulk reduction [21].



**Figure 3.2: Topology optimized and additive manufactured Airbus A320 nacelle hinge bracket (initial bracket (a) and optimized bracket (b)) [29]**

### **3.1.2 Case Study of Brackets on a Turbodiesel Aviation Engine**

A potent set of tools for designing and producing highly optimized, complicated components may be created by combining AM and TO. The two pieces that can be created by conventional methods have been combined into one piece for the purposes of this thesis, and a topology optimization appropriate for additive manufacturing has been made. The bracket components utilized in a turbodiesel aviation engine are explained as a case study. With this work, the parts were lighter by means of TO and a more complex part could be produced by means of AM, thus eliminating the need for bolting between the parts.

Exact dimensions are considered as confidential information of TEI and can not be provided here. The manipulated brackets geometries weigh about 350 grams and are shown in Figure 3.3. In the scope of the study, the interfaces of the bracket parts were preserved. The work was completed without the need to make any changes to the interface parts. Bolt connections and types are preserved.



**Figure 3.3: Non-Optimized Brackets**

Inconel Alloy 625 is a nickel-based superalloy with exceptional strength and resilience to high temperatures. Additionally, it offers excellent resistance to corrosion and oxidation. It is the perfect option for a number of industrial applications due to its ability to withstand high stress, a broad range of temperatures, both in and out of water, as well as prevent corrosion when subjected to severely acidic environments.

Inconel 625 alloy's superior and adaptable corrosion resistance under a wide range of temperatures and pressures is a main reason for its widespread popularity in the chemical processing area. It is used in a range of plant equipment components because to its simplicity of manufacture. Inconel 625 alloy is also used widely in the marine, automobile, aerospace and defence industries.

The material data from the literature search entered manually and used in ANSYS Workbench AM Library for Inconel 625. The physical properties and chemical composition of the material can be seen in [48] and

Table 2.2. Because ANSYS 2019 R1 TO tool only works with linear material properties, this data is an approximation of non-linear material data which is calculated in ANSYS Workbench AM Library.

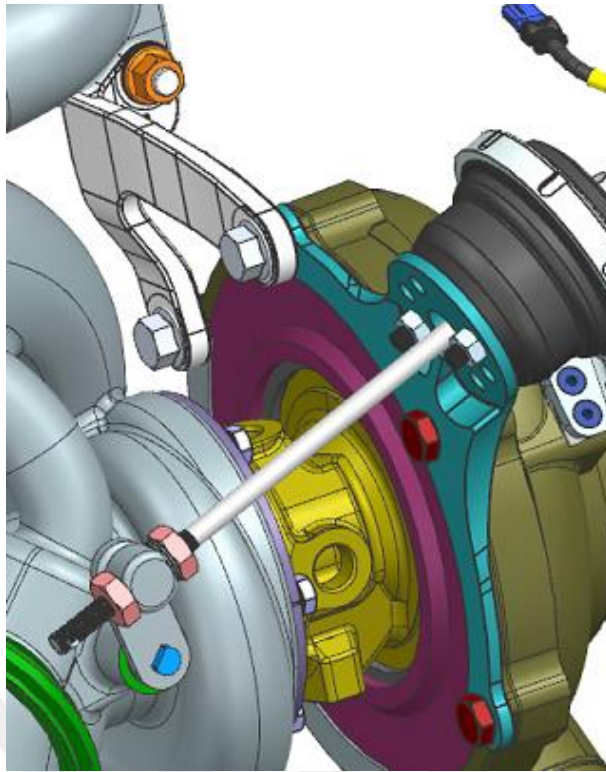
**Table 3.1: Chemical Composition of INCONEL 625 [48]**

Component	Ni	Cr	Mo	Fe	C	Nb+Ta	
Wt. %	58	20-23	8-10	5	0.10	3.15-4.15	
Component	Mn	Si	Al	Ti	S	P	Co
Wt. %	0.50	0.50	0.40	0.40	0.015	0.015	1

**Table 2.2: Material Data for INCONEL 625**

Property	Value	Unit
Density	8440	kgm <sup>-3</sup>
Coefficient of Thermal Expansion	1,31x10 <sup>-5</sup>	C <sup>-1</sup>
Young's Modulus	1,49 x10 <sup>11</sup>	Pa
Poisson's Ratio	0,2875	
Isotropic Thermal Conductivity	12,5	Wm <sup>-1</sup> C <sup>-1</sup>
Maximum Service Temperature	982	°C
Ultimate Tensile Stress @25°C	957	Mpa
%0,2 Yield Stress @25°C	496	Mpa

Interface parts could not be included in the study due to information confidentiality. Only bracket parts were analyzed. Bolt and nut parts for bolt preloads are simplified and included in the analysis.



**Figure 3.4: Illustration of brackets and interface parts**

### **3.2 Methodology**

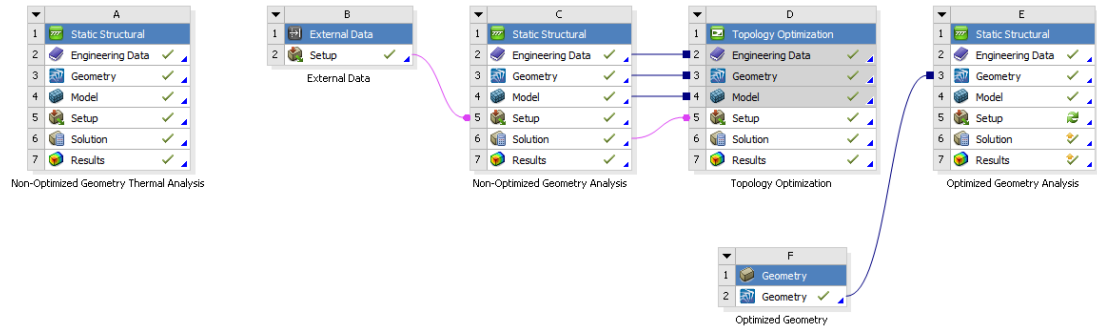
The fundamental TO approach takes into account an initial geometry with a bigger design space. After each iteration, material is deleted (or added) until the analysis's goal is fulfilled, at which point the final material arrangement is obtained. To optimize this using TO, one technique is to specify the portion with a bigger volume than the original geometry. The TO program can provide an optimum and more valuable design after applying the loads, restrictions, and objectives.

Another option is to utilize a TO on the existing geometry without adding any extra volume or mass. In this thesis, ANSYS program was used to perform this technique. The output geometry as the optimization result can be accomplished by the software settings and restrictions that are defined at the start of the optimization process as an input for both techniques.

In this study, Simens NX 12 was used for model manipulations, simplifications and preparations, and ANSYS Workbench 2019 R1 was used for static structural analysis and topology optimization studies.

### 3.2.1 Analysis Setup

In this work, TO received precedence. Static structural comparisons between the original and optimized brackets were conducted. All analyses performed with order as seen in Figure 3.5.



**Figure 3.5: Analysis flowchart**

The case study brackets where the investigation was conducted contain temperature loads, bolt pretension loads, and acceleration loads. Thermal loads are not supported by topology optimization tools in ANSYS. Due to this, a thermal study was initially carried out on the components when they were in a steady state. The outcome of this study was then transferred into the static structural analysis, which did not examine any additional loads operating on the component.

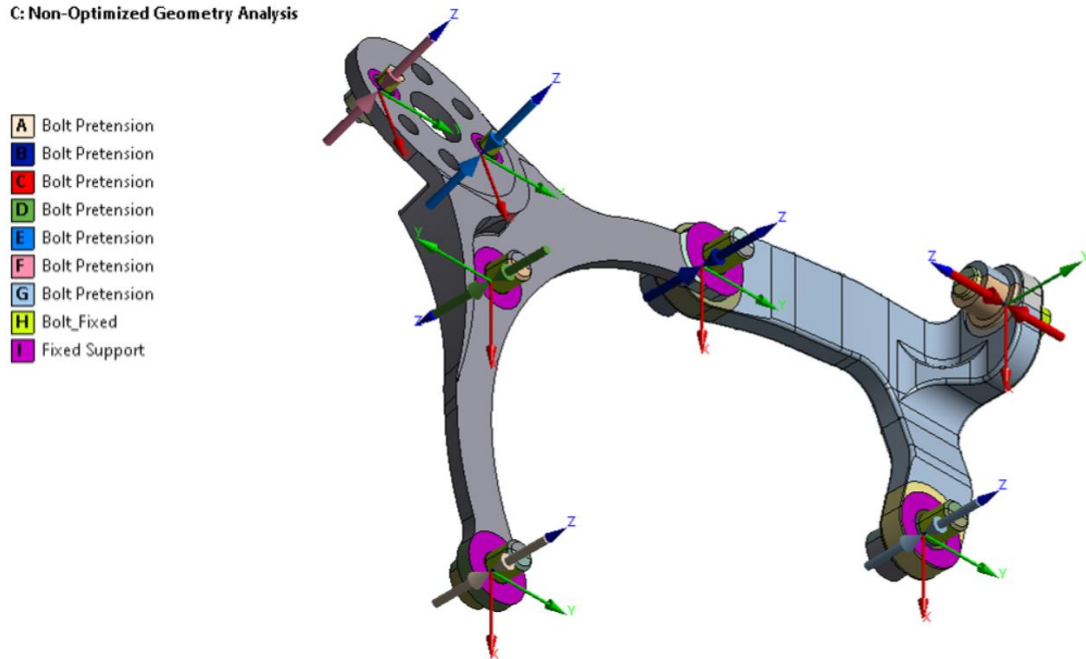
Static structural analysis have been finished with the boundary conditions and loads that are discussed in the next sections. The TO was examined using the results of this research, and the optimization parameters are discussed in the following sections.

The geometry that was produced by the optimization process was modified for analysis and to make it a manufacturable parts. Static structural analysis was used to verify the modified components.

### 3.2.2 Boundary Conditions and Loading

Bracket parts are fixed from existing interface locations. In addition, the bolt and nut parts on the parts are fixed and bolt pretension values are given to the bolts according to the design. The values are regarded as TEI-confidential information and cannot be shown in the thesis.

### C: Non-Optimized Geometry Analysis



**Figure 3.6: Boundary conditions and loading of the brackets**

Static structural analyzes are solved in 3 steps. Firstly, the bolts are torqued, secondly, the initial stresses due to thermal loads are added to the model. Finally, the maximum acceleration force is applied to the brackets within the design limits.

### 3.2.3 Meshing

The element size must be less than the smallest dimension of each component in the recommended geometry in order to execute an accurate analysis and obtain well-defined accuracy during the analysis. This results in more finite element meshes for structures with tiny volume fractions. By selecting a finer mesh for complicated geometries to boost optimization effectiveness and a coarser mesh for other geometries for accurate analysis, the mesh is adjusted to minimize the number of components. To guarantee well-defined accuracy, it is better to have several mesh components along the finest geometry.

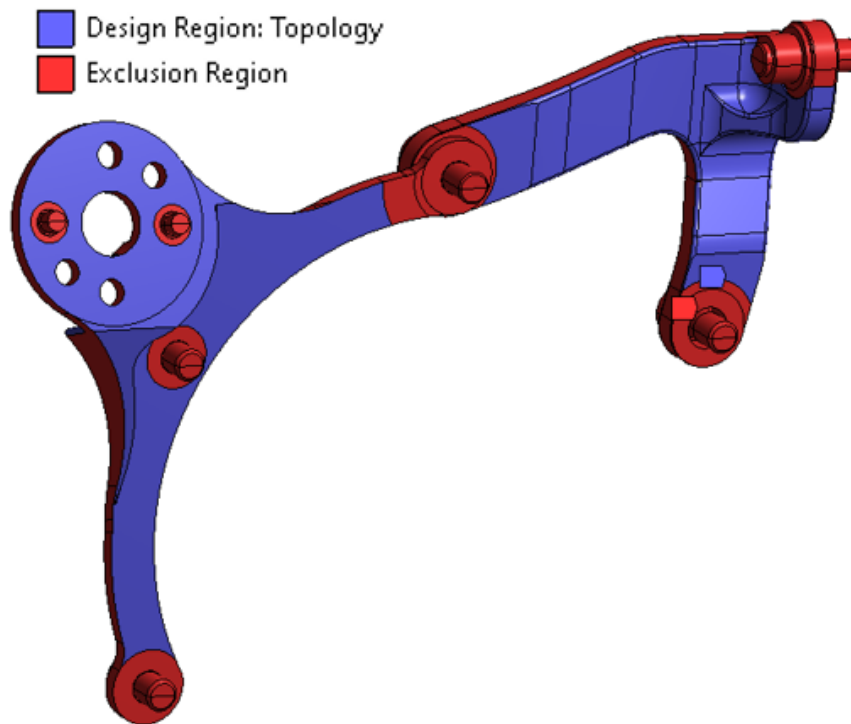
1 mm size tetrahedron type mesh was used in brackets. Hex Dominant mesh was used in bolts. Mesh quality is improved with face meshing and edge sizing commands on complex surfaces of parts. As a result, there are more than 110000 nodes, more than 475000 elements on the model.



**Figure 3.7: Mesh model of the brackets**

### **3.2.4 Topology Optimization Parameters**

In order to utilize TO in ANSYS, it is necessary to make some settings and use parameters. First of all, the regions to be optimized and not to be optimized are selected. In this design, the bolted-joint regions are selected as the interface location and will be excluded from the optimization so that it does not affect the current design. In this way, the connection design of the parts is protected by preventing change. Design and exclusion regions are shown in Figure 3.8.



**Figure 3.8: Design and exclusion region of the brackets**

In the analysis settings of the static structure, the large deviation option in the solver controls section and the solver units in the analysis data management section must be correctly defined to be on the safe side. The large deflection option is set to off for all linked analyses, because topology optimization does not support choosing a solution with large deformation on. Solver units were set as active system to avoid unit system mismatch between environments included in the solution. There are a few input options that may be defined for the solver algorithm in ANSYS TO's analysis settings. The default setting for the maximum iterations is 500. The minimum normalized intensity was set to 0.001, and the convergence accuracy was set to 0.1% by default.

Based on the topological density determined during solution, the penalty factor was utilized to scale the stiffness of the structure matrix of each element from 0 to 1. The matrix of stiffness is weighted more toward pieces with a density near to 1 as the Penalty Factor increases, reducing the amount of room for error in the final design. The less gray zone, the better and lighter the design. In this thesis, the penalty factor is set to 3. In this thesis, minimizing compatibility, which is a standard terminology

in TO, was chosen as the aim. This is the opposite of maximizing stiffness. The other two goals are minimizing volume and mass.

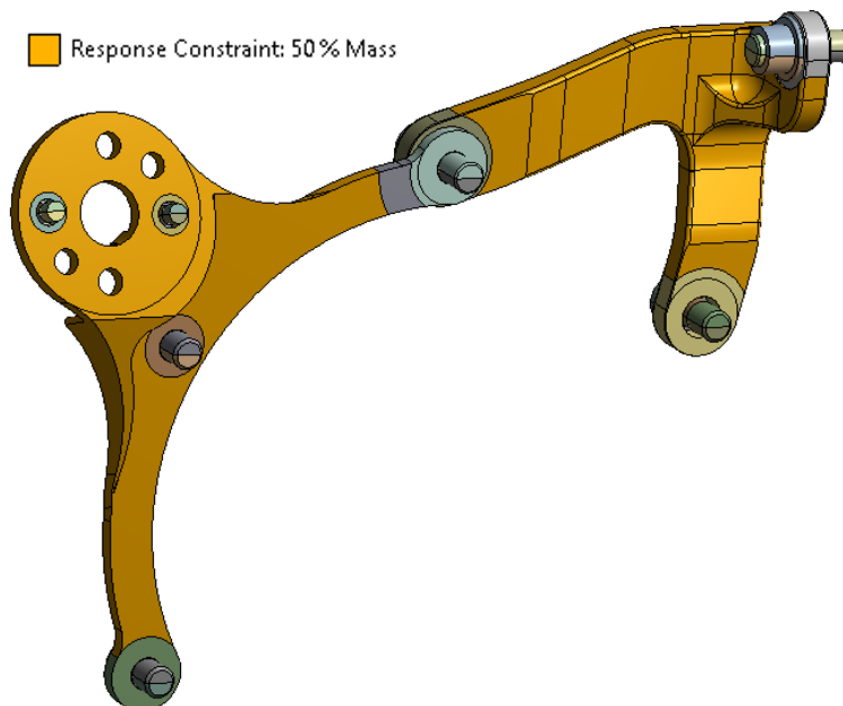
In this study, mass was chosen as the response constrain. Optimization study was carried out by limiting the minimum retain value to 50% margin value in the parts to be optimized. Regions to be optimized for topology were selected as regions for weight reduction.

Enabled	Response Type	Goal	Formulation	Environment Name	Weight	Multiple Sets	Start Step	End Step
<input checked="" type="checkbox"/>	Compliance	Minimize	Program Controlled	Static Structural	1	Enabled	1	3

**Figure 3.9: Objective of topology optimization**

Details of "Response Constraint"	
<b>Scope</b>	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
<b>Definition</b>	
Type	Response Constraint
Response	Mass
Define By	Constant
<input type="checkbox"/> Percent to Retain	50 %
Suppressed	No

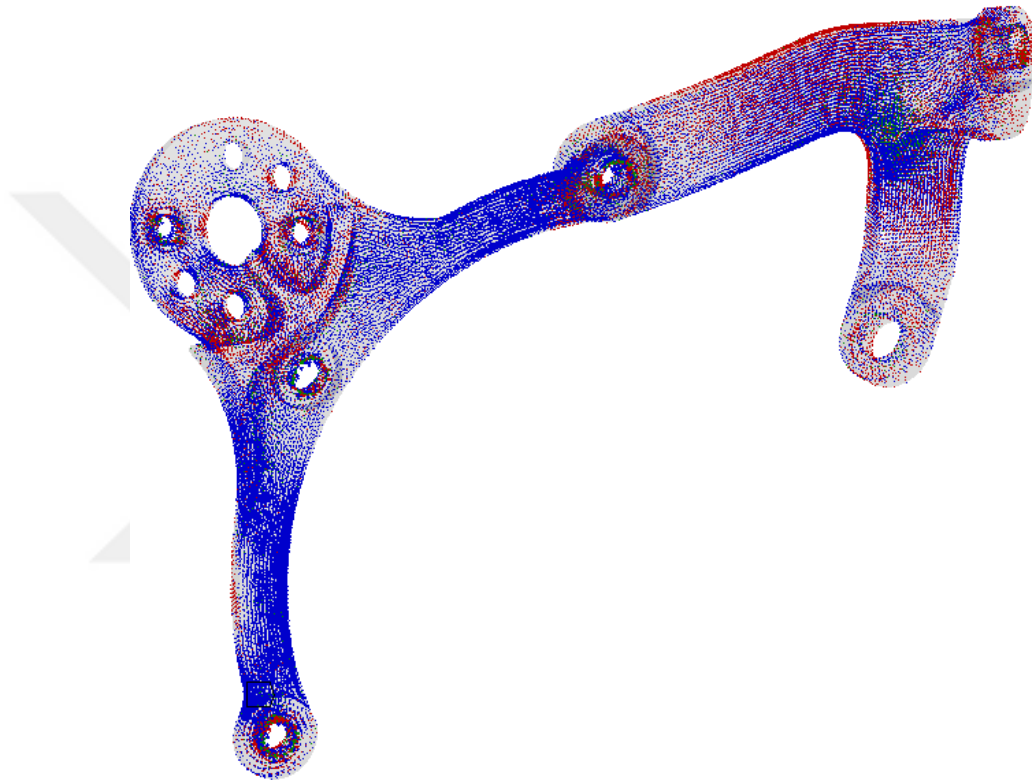
**Figure 3.10: Details of response constraint**



**Figure 3.11: Location of response constraint**

## 4 RESULTS

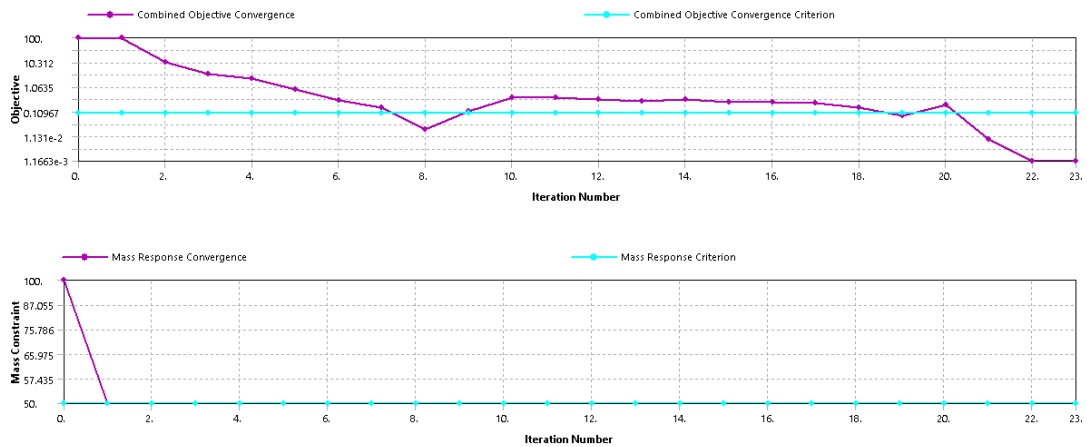
Structural analysis and TO studies were completed within the design requirements of the parts. Structural analysis of the existing parts was completed before TO. Since TO could not be performed with thermal data inputs, thermal analysis of the brackets was performed first. The result of this analysis was imported into the static structural analysis as initial stress as external data as shown in Figure 4.1.



**Figure 4.1: Imported initial stress of brackets**

Non-optimized models with initial stresses, maximum acceleration load and bolt pretension loads were analyzed. The following sections provide an in-depth discussion of the analyses' findings.

After this study, TO studies were carried out. According to the criteria described in the previous sections, the TO analysis converged at the 23rd iteration (Figure 4.2).



**Figure 4.2: Iteration number of topology optimization**

The geometry obtained as a result of the TO study is seen in Figure 4.3. This figure only shows the change in the optimized regions, the regions not included in the study are not included in the Figure 4.3. Since the obtained geometry was formed by the SIMP method, elements remained in some locations. These elements need to be cleaned.



**Figure 4.3: Optimization result of brackets**

Choosing a maintained threshold value was a crucial step in assessing the optimization outcome. Lower numbers denote unnecessary content that may be

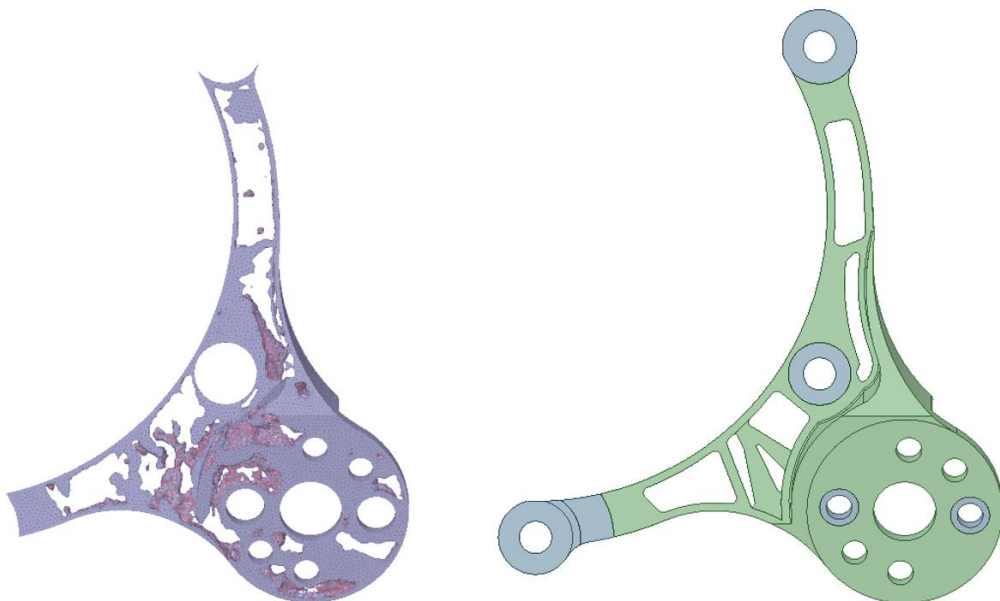
deleted, whereas higher values denote material that must be maintained. Following comparisons between several threshold values, a default value of 0.5 was chosen, where the outcome represents a continuous structure.

As a result of the study, the weight of the topology optimized brackets decreased by approximately 50%. While the mass of the current design was approximately 353.53 grams, it decreased to 191.73 grams as a result of the study. The change between the initial and final design is seen in Figure 4.4.

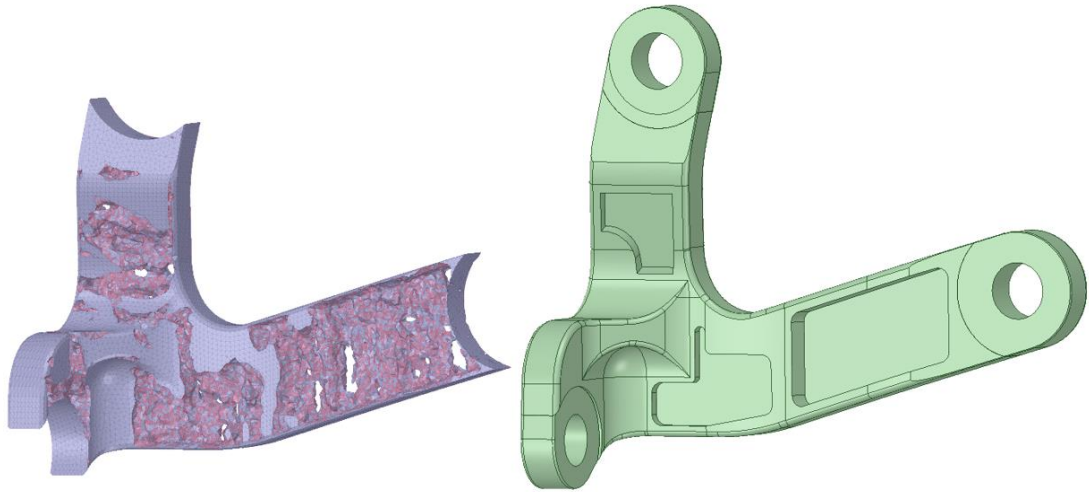
<b>Results</b>	
<input type="checkbox"/> Minimum	0.18904
<input type="checkbox"/> Maximum	1.
<input type="checkbox"/> Average	0.56634
<input type="checkbox"/> Original Volume	41887 mm <sup>3</sup>
<input type="checkbox"/> Final Volume	22717 mm <sup>3</sup>
<input type="checkbox"/> Percent Volume of Original	54.234
<input type="checkbox"/> Original Mass	0.35353 kg
<input type="checkbox"/> Final Mass	0.19173 kg
<input type="checkbox"/> Percent Mass of Original	54.234

**Figure 4.4: The changing between original and final design**

The geometry obtained after TO is not a geometry that can be directly used, analyzed and produced. For this reason, the relevant geometry needs to be edited. The geometry obtained in this thesis was edited through ANSYS SpaceClaim. Figures 4.5 and 4.6 display the TO analysis-generated design on the left and the revised design on the right, respectively.



**Figure 4.5: Topology optimized bracket 1 and re-designed bracket 1**



**Figure 4.6: Topology optimized bracket 2 and redesigned bracket 2**

After the geometries obtained after TO were re-designed, structural analysis was performed. The inputs and boundary conditions in this analysis are exactly the same as the analysis performed before the optimization study. The only difference is that in the analysis after the optimization study, the thermal loads of the geometries are not imported for the analysis as initial stress. In this analysis, thermal analysis was applied directly to the new geometries. The analysis results of the optimized and pre-optimized brackets are shown in detail in Sections 4.1 and 4.2. In both analyses the Von Mises criterion was used.

#### **4.1 Non-Optimized Bracket Analysis**

According to the analyses performed before the TO, the highest is seen at the point where the two brackets meet. However, this region was simplified for high mesh quality and left as a sharp corner. There is a singularity due to the sharp corner and this is the reason for the highest stress. Since the brackets do not usually operate under extreme conditions, no high stress was observed. The Von Mises stresses and displacements of the geometries are as seen in Figure 4.7 and 4.8.

C: Non-Optimized Geometry Analysis  
Equivalent Stress  
Type: Equivalent (von-Mises) Stress  
Unit: MPa

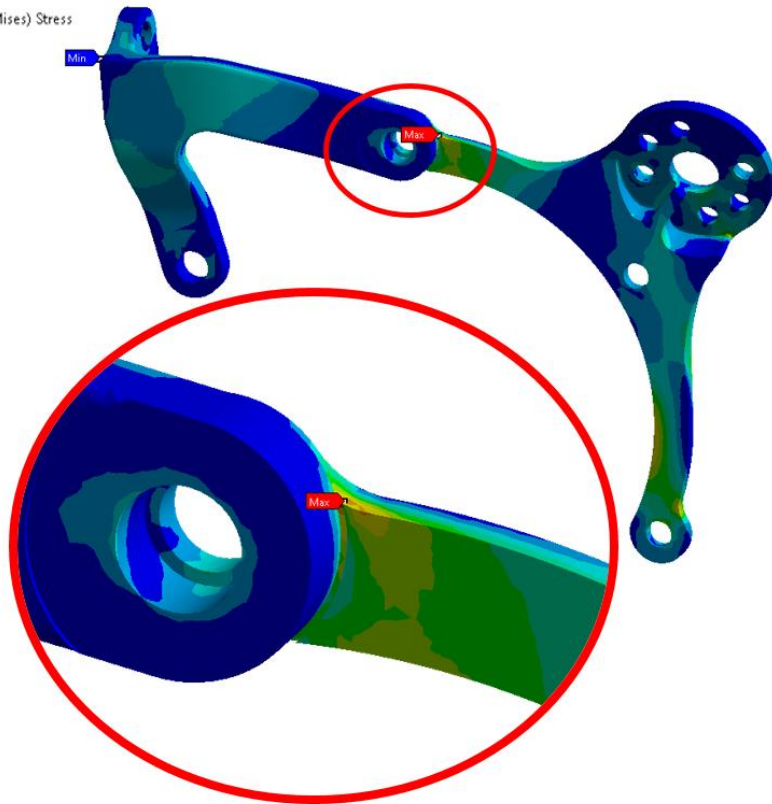
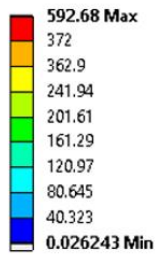


Figure 4.7: Von Mises stress of non-optimized brackets

C: Non-Optimized Geometry Analysis  
Total Deformation  
Type: Total Deformation  
Unit: mm

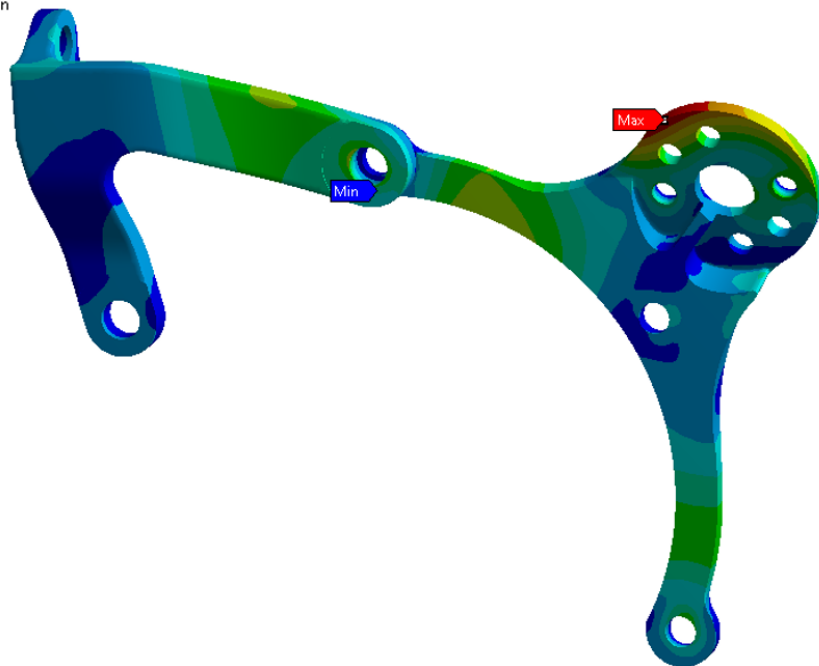
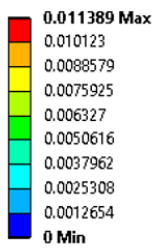
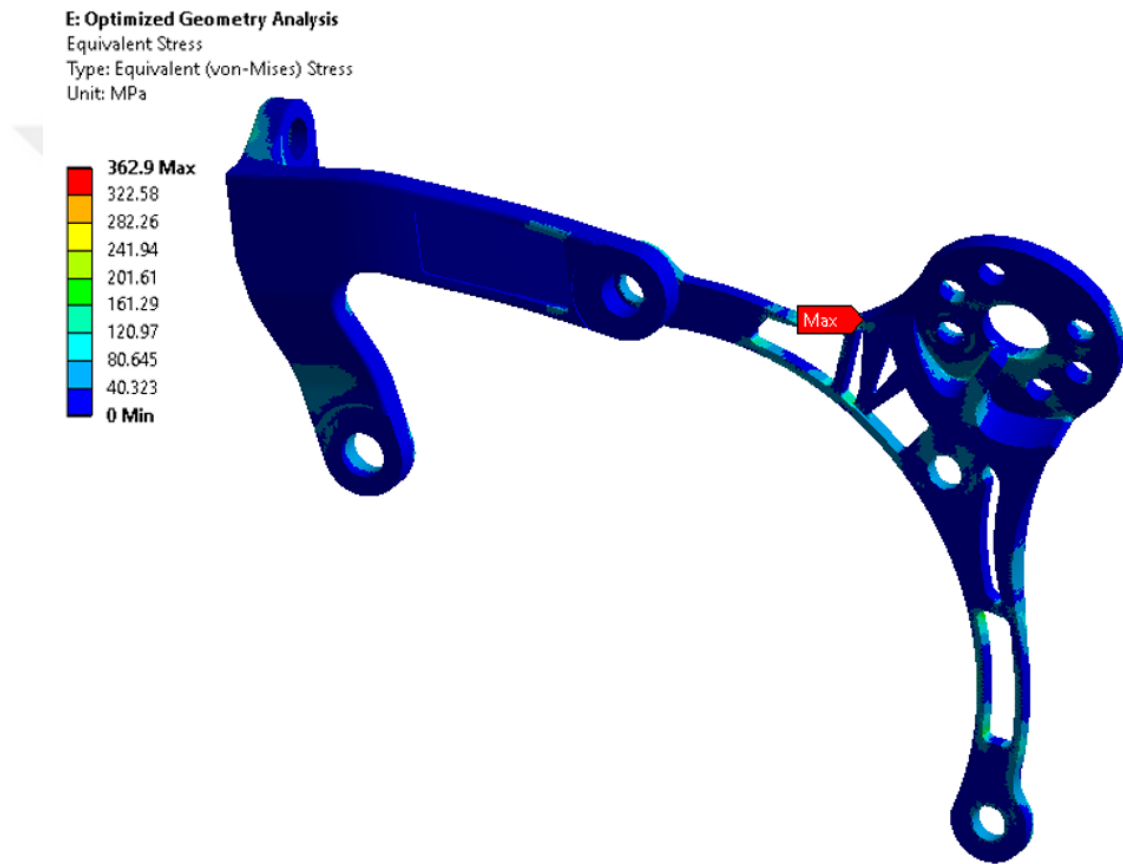


Figure 4.8: Deformation of non-optimized brackets

## 4.2 Topology Optimized Bracket Analysis

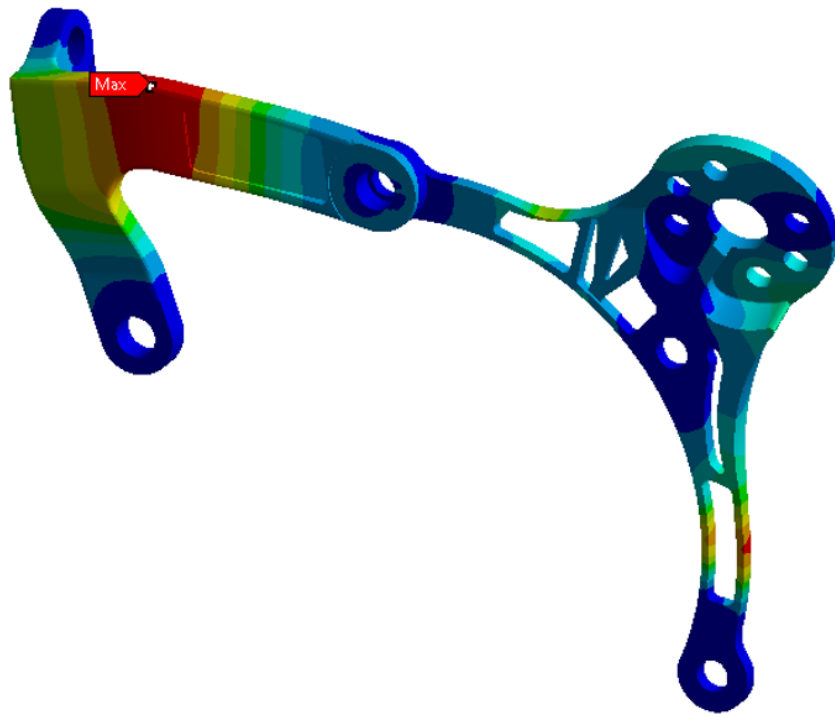
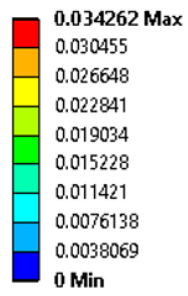
The stress and displacement results for the geometry resulting from the TO are shown in Figure 4.9 and 4.10. The yield strength of the component at 200°C of 372 MPa, whereas the maximum stress in the brackets is 363 MPa. These results show that while the strength of the design has not deteriorated, the displacements have increased and weight have decreased. Since the displacement difference is negligible in terms of design, no re-optimization study was performed. In addition, with the new one-part design, both assembly is easier and manufacturing time is reduced.



**Figure 4.9: Von Mises stress of optimized brackets**

**E: Optimized Geometry Analysis**

Total Deformation  
Type: Total Deformation  
Unit: mm



**Figure 4.10: Deformation of optimized brackets**

## 5 CONCLUSION AND FUTURE SCOPE

With this study, it was aimed to show that lighter designs, which are very important for the aviation industry, can be achieved with the combination of TO and AM. In addition, it was shown that these improvements can be made not only with a single object, but also by integrating multiple objects. For this purpose, bracket parts of a turbo diesel aviation engine were selected as the case study. At the end of the study, a design that is both lighter, easier to assemble and no worse than the existing design in terms of strength was realized.

Nowadays, with the advancement of technology, AM possibilities are expanding. However, as optimization softwares develops in the near future, topology optimization-additive manufacturing collaboration will grow tremendously. Engineers will be able to solve optimization issues faster, with lighter components that are more resilient, and without having to consider some manufacturing limits.

In this project, a design was created using a sample component from the aviation sector using TO and AM. Although the weights of the pieces were lowered overall in this design research, there was no noticeable loss in the strength of the parts. Furthermore, using TO and AM technologies, two components are created as one. As a result, the engine's mountability and maintainability have been improved. Furthermore, because it is one component rather than two, the number of parts that must be approved has been reduced. There are also several advantages, such as a reduction in production mistakes, a shortening of the production time, and an improvement in engine performance because of weight is lowered.

This study can be enhanced in future studies by comparing it to alternative optimization programs. Furthermore, if a design is produced from scratch, multiple design choices might be created by leveraging generative design chances. With the advancement of artificial intelligence, generative design designs will improve even further. In addition, studies can be planed as a future work on the qualification process, component, equipment and engine tests of the parts produced by AM in the aviation sector.

## REFERENCES

- [1] ASTM Standard, (2012), “Standard Terminology for Additive Manufacturing Technologies”, vol. 10.04.
- [2] Antonysamy A., (2012), “Microstructure, Texture and Mechanical Property Evolution during Additive Manufacturing of Ti6Al4V Alloy for Aerospace Applications”.
- [3] Bendsoe m. P., Sigmund O., (2003), “Topology optimization: theory, methods, and applications”, Springer Science & Business Media.
- [4] Chen C., Wang X., Wang Y., Yang D., Yao F., Zhang W., Wang B., Sewvandi G.A., Yang D., Hu D., (2020), “Additive manufacturing of piezoelectric materials”, *Advanced Functional Materials*, 2020,30, 2005141.
- [5] Gradl P.R., Protz C.S., (2020), “Technology advancements for channel wall nozzle manufacturing in liquid rocket engines”, *Acta Astronaut.* 174 148–158.
- [6] Gradl P.R., Protz C.S., Wammen T., (2019), “Additive manufacturing and hot-fire testing of liquid rocket channel wall nozzles using blown powder directed energy deposition inconel 625 and JBK-75 alloys”.
- [7] Gradl P.R., Protz C.S., Zagorski K., Doshi V., McCallum H., (2019), “Additive manufacturing and hot-fire testing of bimetallic GRCop-84 and C-18150 channel-cooled combustion chambers using powder bed fusion and inconel 625 hybrid directed energy deposition”.
- [8] Gibson I., Rosen D., Stucker B., (2015), “Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing, second edition”, *Addit. Manuf. Technol. 3D Printing, Rapid Prototyping, Direct Digit. Manuf. Second Ed.*, no. 3, pp. 1–498.
- [9] ISO/ASTM 52900, (2015), “Additive manufacturing - General principles – Terminology”.
- [10] Kumar L.J., Nair C.G. K., (2017), “Current trends of additive manufacturing in the aerospace industry”, *Advances in 3D Printing & Additive Manufacturing Technologies*, Springer Singapore, Singapore, pp. 39– 54.
- [11] Kelly S.M., Kampe S.L., (2004), “Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part II”, *Thermal modeling, Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.* 35 (6) 1869–1879.
- [12] Kelly S.M., Kampe S.L., (2004), “Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part I”, *Microstructural characterization, Metall. Mater. Trans. A* vol. 35 A, 6 1861–1867.
- [13] Loy J., Tatham P., (2016), “Redesigning production systems, Environ”, *Footprints Eco-Des. Prod. Process*, 145–168.
- [14] Leary M., (2019), “Design for additive manufacturing”.
- [15] Liu J. et al., (2018), “Current and future trends in topology optimization for additive manufacturing”, *Struct. Multidiscip. Optim.*, vol. 57, no. 6, pp. 2457–2483.
- [16] Langelaar M., (2017), “An additive manufacturing filter for topology optimization of print-ready designs”, *Struct. Multidiscip. Optim.*, vol. 55, no. 3, pp. 871–883.
- [17] Liu R., Wang Z., Sparks T., Liou F., Newkirk J., (2017), “Aerospace applications of laser additive manufacturing”, *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*, Elsevier, pp. 351–371.

- [18] Moustafa A.M, (2018), “A Multilayer Optimization Scheme for Lattice Steel Structures”.
- [19] Wohlers Report 2014, (2014), “3D Printing and Additive Manufacturing State of the Industry”, Annual Worldwide Progress Report, Wohlers Associates.
- [20] Milner B. B., Gradl P., Snedden G. Brooks M., Pitot J., Lopez E., Leary M., Berto F., Plessis A. D., (2021), “Metal additive manufacturing in aerospace: A review”, *Materials & Design*, Volume 209, 110008.
- [21] Meng L., Zhang W., Quan D., Shi G., Tang L., Hou Y., Breitung P., Zhu J., Gao T., (2020), “From topology optimization design to additive manufacturing: today’s success and tomorrow’s roadmap”, *Arch. Comput. Methods Eng.* 27 (3) 805–830.
- [22] Orme M.E., Gschweidl M., Ferrari M., Vernon R., Madera I.J., Yancey R., Mouriaux F., (2017), “Additive manufacturing of lightweight, optimized, metallic components suitable for space flight”, *J. Spacecraft Rockets* 54 (5) 1050–1059.
- [23] Orme M. E., Gschweidl M., Ferrari M., Madera I., Mouriaux F., (2017), “Designing for additive manufacturing: lightweighting through topology optimization enables lunar spacecraft”, *J. Mech. Des., Trans. ASME* 139 (10).
- [24] Pragana J.P.M., Sampaio R.F.V., Bragança I.M.F., Silva C.M.A., Martins P.A.F., (2021), “Hybrid metal additive manufacturing: A state-of-the-art review”, *Advances in Industrial and Manufacturing Engineering*, Volume 2.
- [25] Pereira J.C., Borovkov H., Zubiri F., Guerra M.C., Caminos J., (2021), “Optimization of thin walls with sharp corners in SS316L and IN718 alloys manufactured with laser metal deposition”, *J. Manuf. Mater. Process.* 5 (1) 5.
- [26] Paolini A., Kollmannsberger S., Rank E., (2019), “Additive manufacturing in construction: A review on processes, applications, and digital planning methods”, *Additive Manufacturing*, Volume 30, 100894.
- [27] Rochus P., Plessier J. Y., Elsen M. V., Kruth J. P., Carrus R., Dormal T., (2007), “New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation”, *Acta Astronaut.* 61 (1–6) 352–359.
- [28] Steinbuch R., Gekeler S., (2016), “Bionic Optimization in Structural Design, Stochastically Based Methods to Improve the Performance of Parts and Assemblies” Berlin, Springer.
- [29] Tomlin M., Meyer J., (2011), “Topology optimization of an additive layer manufactured (ALM) aerospace part”, *The 7th Altair CAE Technology Conference*, pp. 1–9, 2011.
- [30] Uriondo A., Esperon-Miguez M., Perinpanayagam S., (2015), “The present and future of additive manufacturing in the aerospace sector: a review of important aspects”, *Proc. Inst. Mech. Eng., Part G: J. Aerospace Eng.* 229 (11) 2132–2147.
- [31] Vasco J. C., (2021), “Additive manufacturing for the automotive industry”, In *Additive Manufacturing* (pp. 505-530), Elsevier.
- [32] Vignesh M., Ranjith K. G., Sathishkumar M., Manikandan M., Rajyalakshmi G., Ramanujam, R., Arivazhagan N. (2021), “Development of biomedical implants through additive manufacturing: A review”, *Journal of Materials Engineering and Performance*, 30, 4735-4744.
- [33] Wang F., Williams S., Colegrove P., Antonysamy A.A., (2013), “Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V”, *Metall. Mater. Trans. A* 44 (2) 968–977.
- [34] Yu J., Rombouts M., Maes G., Motmans F., (2012), “Material properties of Ti6Al4V parts produced by laser metal deposition”, *Phys. Proc.* 39 416–424.

- [35] Web 1, (2022), <http://www.xtreee.eu>, (Accessed: 24.04.2022).
- [36] Web 2, (2022), <https://www.tue.nl/en/research/research-groups/structural-engineering-and-design/3d-concrete-printing>, (Accessed: 14.04.2022).
- [37] Web 3, (2022), <https://www.grandviewresearch.com/industry-analysis/healthcare-additive-manufacturing-market>, (Accessed: 14.04.2022).
- [38] Web 4, (2022), <https://www.fastradius.com/resources/how-additive-used-in-automotive-industry/>, (Accessed: 15.04.2022).
- [39] Web 5, (2022), [https://www.eos.info/01\\_parts-and-applications/\\_parts/\\_case\\_studies\\_applications/\\_parts/\\_case\\_studies\\_pdf/en\\_cases/cs\\_m\\_aerospace\\_ruag\\_en.pdf](https://www.eos.info/01_parts-and-applications/_parts/_case_studies_applications/_parts/_case_studies_pdf/en_cases/cs_m_aerospace_ruag_en.pdf), (Accessed: 15.04.2022).
- [40] Web 6, (2022), [https://www.eos.info/01\\_parts-and-applications/case\\_studies\\_applications/\\_parts/\\_case\\_studies\\_pdf/en\\_cases/cs\\_m\\_aerospace\\_arianegroup\\_en.pdf](https://www.eos.info/01_parts-and-applications/case_studies_applications/_parts/_case_studies_pdf/en_cases/cs_m_aerospace_arianegroup_en.pdf), (Accessed: 15.04.2022).
- [41] Web 7, (2022), <https://www.nasa.gov/exploration/systems/sls/3d-printed-rocket-injector.html>, (Accessed 16.04.2022).
- [42] Web 8, (2022), <https://www.nasa.gov/exploration/systems/sls/3dprinting.html>, (Accessed 16.04.2022).
- [43] Web 9, (2022), <https://optics.org/news/6/4/7>, (Accessed 16.04.2022).
- [44] Web 10, (2022), [https://www.optomec.com/wp-content/uploads/2014/02/Optomec\\_LENS\\_Repair\\_Datasheet.pdf](https://www.optomec.com/wp-content/uploads/2014/02/Optomec_LENS_Repair_Datasheet.pdf), (Accessed 16.04.2022).
- [45] Web 11, (2022), <https://www.metal-am.com/ge-aviation-reaches-milestone-with-100000-fuel-nozzle-tips/>, (Accessed 06.05.2022).
- [46] Web 12, (2022), [https://www.norsktitanium.com/storage/media/NOR18005\\_OverviewBrochure\\_FA1\\_digital.pdf](https://www.norsktitanium.com/storage/media/NOR18005_OverviewBrochure_FA1_digital.pdf), (Accessed 20.06.2022).
- [47] Web 13, (2022), <https://www.airbus.com/en/newsroom/press-releases/2017-09-first-titanium-3d-printed-part-installed-into-serial-production>, (Accessed 20.06.2022).
- [48] Web 14, (2023), <https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-625.pdf>, (Accessed 20.05.2023).
- [49] Zhu J. H., Zhang W. H., Xia L., (2016), “Topology optimization in aircraft and aerospace structures design”, *Arch. Comput. Methods Eng.* 23 (4) 595–622.
- [50] Zhu J. H., Li Y., Zhang W. H., Hou J., (2016), “Shape preserving design with structural topology optimization”, *Struct. Multidiscip. Optim.* 53 (4) 893–906.

## **BIOGRAPHY**

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