UAB
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Industry 4.0 in Aeronautical Manufacturing: The Impact of 3D Printing

Bachelor's Degree in Aeronautical Management

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CERTIFICA:

Que el treball al que correspon la present memòria
ha estat realitzat sota la seva direcció per

Albert Jodar Aranda

I per a que consti firma la present.
Sabadell, ***Juliol de 2024***

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FULL DE RESUM – TREBALL DE FINAL DE GRAU DE L'ESCOLA D'ENGINYERIA

<table>
<tr><td colspan="2">Títol del Treball de Final de Grau:
Industry 4.0 in aeronautical manufacturing: The impact of 3D printing.
Industria 4.0 en la manufactura aeronáutica: El impacto de la impresión 3D.
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<tr><td>Autor: Albert Jodar Aranda</td><td>Data: Juliol 2024</td></tr>
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English: The present work discusses how technologies that have emerged from Industry 4.0, with a special emphasis on 3D Printing, also known as Additive Manufacturing, are having and will have a positive impact on the production and logistics systems of companies in various sectors, such as the aerospace or aircraft industry. The work details the different technologies that are part of this industrial revolution, as well as the potential impact of effectively implementing one of them, such as 3D Printing, in a current aerospace manufacturer.
Español: El presente trabajo trata sobre cómo las tecnologías que han emergido de la Industria 4.0, con especial énfasis en la Impresión 3D, también conocida como Fabricación Aditiva, están teniendo y tendrán un impacto positivo en los sistemas productivos y logísticos de empresas de diversos sectores como es el aeroespacial o aeronáutico. En el trabajo se detalla las diferentes tecnologías que forman parte de dicha revolución industrial, así como el impacto potencial que sería implementar una de ellas, como es la Impresión 3D, de forma efectiva en un productor aeronáutico actual.</td></tr>
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- **Català:** El present treball tracta sobre com les tecnologies que han emergit de la Indústria 4.0, amb especial èmfasi en la Impressió 3D, també coneguda com a Fabricació Additiva, estan tenint i tindran un impacte potencialmente positiu en els sistemes productius i logístics d'empreses de diversos sectors com l'aeroespacial o l'aeronàutic. En el treball es detallen les diferents tecnologies que formen part d'aquesta revolució industrial, així com l'impacte que seria implementar-ne una, com és la Impressió 3D, de manera efectiva en un productor aeronàutic actual.

List of Abbreviations and Acronyms

- **3D -** *Three Dimension*
- **AI -** *Artificial Intelligence*
- **AM -** *Additive Manufacturing*
- **AR -** *Augmented Reality*
- **DMLS -** *Direct Metal Laser Sintering*
- **EBF3 -** *Electron Beam Freeform Fabrication*
- **EBM -** *Electron Beam Melting*
- **ERP -** *Enterprise Resource Planning*
- **FDM -** *Fused Deposition Modeling*
- **IIoT -** *Industrial Internet of Things*
- **IoT -** *Internet of Things*
- **LMD -** *Laser Metal Deposition*
- **MD -** *Metal Deposition Process*
- **ML -** *Machine Learning*
- **MRO -** *Maintenance, Repair, Operations*
- **OEM -** *Original Equipment Manufacturer*
- **PLM -** *Product Lifecycle Management*
- **SCM -** *Supply Chain Management*
- **SLA -** *Stereolithography*
- **SLS -** *Selective Laser Sintering*
- **VR -** *Virtual Reality*
- **WAAM -** *Wire and Arc Additive Manufacturing*

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1. Introduction

The objective of this final degree project is to explain the various technologies that have been gaining traction in recent years and are increasingly being implemented by companies across different sectors. Technologies such as Big Data, Artificial Intelligence (AI), and 3D printing are becoming more prevalent in various industrial sectors due to the numerous advantages they bring to production processes [6,7,8]. These advantages include cost savings, digitalization and optimization of processes leading to better management of internal production, improvements in services and final products, and environmental sustainability, which is a highly relevant topic today. [10]

The chosen topic is highly relevant as sectors like the aeronautical industry have readily adopted these technologies, part of a new industrial revolution characterized by digitization and automation [7]. This project is necessary, original, and not obvious for several reasons. Firstly, it addresses the urgent need for the aeronautical industry to adopt cutting-edge technologies to remain competitive and sustainable. The originality lies in focusing specifically on 3D printing, or Additive Manufacturing (AM), within the aerospace sector, a subject not extensively explored in existing literature. This study delves into the practical applications and impacts of AM, offering new insights and potential solutions to current challenges faced by aerospace manufacturers, such as fuel cost reduction, aircraft weight management, and supply chain and value chain improvements.

The main objective of this work is to explore how these technological innovations have recently gained popularity and are being used by manufacturers in the aeronautical sector. The focus will be on 3D printing due to its multiple advantages in production processes and the benefits that components created by this technology can provide to the industry. The work begins with an extensive bibliographic search to understand new technologies from Industry 4.0, such as 3D printing, and contemporary concerns like environmental issues, optimization, digitization, and enhancing product and service performance.

Following this, the project includes a case study of an aeronautical manufacturer, focusing on how the company currently uses AM and how it could further utilize it. This includes examining the impacts on vital parts of the company's logistics, such as the supply chain.

In conclusion, this work aims to contribute to the understanding and implementation of AM in the aerospace sector, showcasing its potential to revolutionize production processes and improve overall industry efficiency and sustainability. The study's findings are intended to be a valuable resource for industry professionals, academics, and policymakers interested in the future of aerospace manufacturing.

1.1. Motivation

The aviation sector is nowadays, one of the most dynamic and innovative sectors of the world. The industry is a prime example that it is constantly pushing the boundaries of innovation. From design and manufacturing to operation and maintenance, advancements are continuously sought to improve efficiency, safety, and performance. Industry 4.0 which is characterized by automation, data exchange, and digitization, presents a transformative opportunity for this dynamic field.

By integrating cutting-edge technologies like the Internet of Things (IoT), Big Data analytics, robotics, and AM, Industry 4.0 promises to streamline processes within the aviation industry. This can encompass aspects like:

- **Enhanced manufacturing:** Utilizing automation and connected machines can optimize production lines, reducing errors and lead times. 3D printing allows for the creation of complex, lightweight parts on-demand, further enhancing efficiency.
- **Predictive maintenance:** Sensors embedded in aircraft can collect real-time data such as temperature, energy consumption, pressure, oil/lubricant condition (...) to predict potential issues and schedule maintenance proactively, minimizing downtime.
- **Improved logistics and supply chain management:** Data-driven insights can optimize inventory management, ensuring timely delivery of critical parts. 3D printing offers the potential for localized production of certain parts, reducing reliance on traditional supply chains.

This confluence of innovation in the aviation sector and new technological advancements create a compelling research area for a bachelor's thesis. By exploring this topic, we can contribute valuable insights into how these advancements are shaping the future of air travel. The potential for improved efficiency [21,27,43], safety [25], and sustainability [24] makes this a particularly intriguing area of study with real-world impact.

Considering this, and with my interest in engineering, aviation and computer science, I think that it is a good point to understand how important it is. Apart from that, I believe that this topic is quite interesting for a bachelor’s degree thesis, as it demonstrates its impact on the current world and its economy, and the beginning of a new technological process that could make a big step in the way we produce and manage products in the future.

1.2. Objectives

For this project, it is important to specify some objectives that it is trying to achieve. It is divided into one general objective, which is decomposed into several specific objectives that will be developed during the work.

1. **General objective:**
   1.1. Developing a case study to explore the advantages offered by new technologies and to observe what impact they can have within a major manufacturer in the aerospace sector. Some of these technologies, such as AM, would be implemented within one of these producers to assess the improvements they offer and determine whether they can provide value to the companies and help enhance their services or products through the implementation of these technologies.

2. **Specific objectives:**
   2.1. Analyze the present technologies from Industry 4.0: advantages, risks, costs and challenges associated.
   2.2. Study the present applications of these technologies in the aeronautical/aerospace sector.
   2.3. Evaluate the potential benefits, challenges and limitations associated with the integration of these technologies in the aviation industry.
   2.4. Identify and critically examine existing applications of Industry 4.0 within the aeronautical/aerospace sector.
   2.5. Identify and discuss challenges, and future applications.
   2.6. Carry out a study case or make an implementation of an aeronautical company relying on the new technological advances.

1.3. Methodology

After presenting the motivation for developing this project and explaining the objectives, it is crucial to detail the methodology that will be followed. First, it is necessary to acquire a deep understanding of the topic, including basic concepts and other useful information for its development. It is essential to understand the terms, information, and context of the situation presented. For the search for relevant information, it is useful to utilize some sources that the Autonomous University of Barcelona (UAB) offers to students for their thesis development.

In this case, the university's database is called "Servei de Biblioteques," created specifically to collect data and theses from various topics and study areas. On this website, there are useful databases that have been used for this work, such as IEEE Xplore and ACM Digital Library, and valuable search tools like Google Scholar, which has been used to find most of the sources for this work. Thanks to all these tools, it has been possible to gather all the necessary information to define the basic concepts for easy comprehension, the technologies used, case studies, the current context, the challenges faced, and future projections. Following this, the various technologies of Industry 4.0 are explained, with a focus on AM, including its different processes, technologies, and applications.

In the second part of the work, a case study centered on the implementation of AM in an aeronautical or aerospace manufacturer is developed, with Airbus being the chosen company. This case study analyzes how Airbus has utilized this technology, what it has been used for, and its contribution to the company from not only an economic perspective but also in terms of operational efficiency, sustainability, and competitiveness. Additionally, the possibility of implementing a component not previously made by 3D printing, such as seatbelt buckles, is studied, explaining the advantages of manufacturing them through this production process.

Finally, a brief discussion of the work is presented, where the results obtained are discussed, followed by a conclusion summarizing the benefits and challenges of AM, its future projection, and some limitations regarding the completion of the work.

1.4. Users

The information presented in this bachelor's thesis could be interesting for the following users:

- Professors and researchers in the field of aeronautical management or engineering.
- Other students who are doing research related to this topic.
- Managers and supply chain professionals in aeronautical companies, manufacturers of parts and components.
- People interested in Industry 4.0 and its technologies.
- People interested in 3D Printing or AM
- General audience like people interested in the aeronautical sector, analysts or investors, aviation enthusiasts.

1.5. Scheduling

For the correct development of this project, I decided to create a chronogram based on a Gantt Diagram using an Excel template. Figure 1 shows each task that this work will follow with the months in different purple colors and the time divided in weeks. The beginning of this project started the day of the first meeting with my tutor, 6th February, and it ends the last day for the oral presentations.

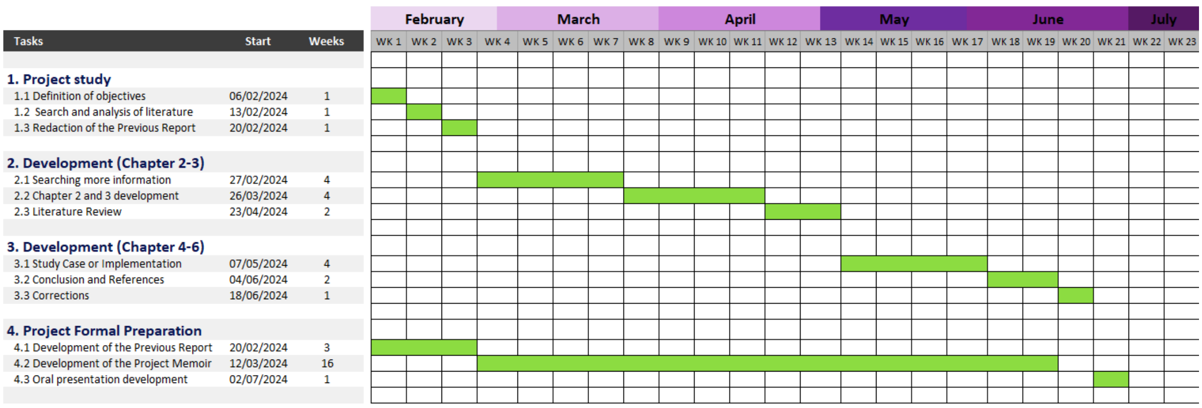

Figure 1. Bachelor's thesis scheduling.

1.6. Risks & Prevention measures for the development

RISK	PREVENTIVE MEASURES
It is needed to read and manage a lot of information to develop a case study, but the main challenge is finding relevant information for a specific case.	Redefining search terms, using advanced search features, and consulting specific resources can help. Academic support may also ease the process.
The topic is wide and complex, with concepts that require technical knowledge to explain.	Explain the topic simply for a general audience. Focus on a specific part to ease project development. Dedicate a section to explain complex concepts.
Some companies don't provide a lot of information about the new features that they implement.	Comparing multiple sources can help resolve this issue.
Finding general information on aviation and Industry 4.0 is easy, but details on current implementation are scarce.	New technologies impact production and supply chains across all sectors similarly. Related information can aid project development.

Table 1. Risks and their preventive measures.

2. Industry 4.0

The purpose of this chapter is to explain the new industrial revolution that has emerged in recent years, providing some context about it. Additionally, it aims to introduce and explain each of the technologies that comprise it. This chapter addresses the digitized and automated nature of this new industry, Industry 4.0. It includes a brief section explaining important logistics concepts. Following this, the chapter provides context on the origin of this industry, its history, and defines it while also outlining several characteristics. Lastly, it delves into the most important aspect: the technologies that comprise it, many of which are currently used in the aerospace sector.

2.1. Basic concepts of Logistics

In this section, some concepts related to logistics will be explained as they are considered interesting or relevant to consider for the development of this work. Concepts such as what logistics and the supply chain, and the differences between the concepts to avoid confusion, are explained below.

2.1.1. Supply chain and its management

The supply chain is a net composed of different organizations, people, activities, information, resources and other processes involved directly or indirectly in the action of satisfying supply needs. This concept is not limited only to manufacturing companies, but has been expanded to include both "tangible products" and "intangible services" that reach the consumer [1].

Supply chain brings a product or service from its origin to the final consumer. It covers all stages of the process, from the extraction of raw materials to the delivery of the finished product, through manufacturing, storage, transportation and distribution.

The supply chain is divided in different phases:

Figure 2 shows the different phases that a simple Supply chain might have. It starts with the raw materials and ends when the customer receives the product.

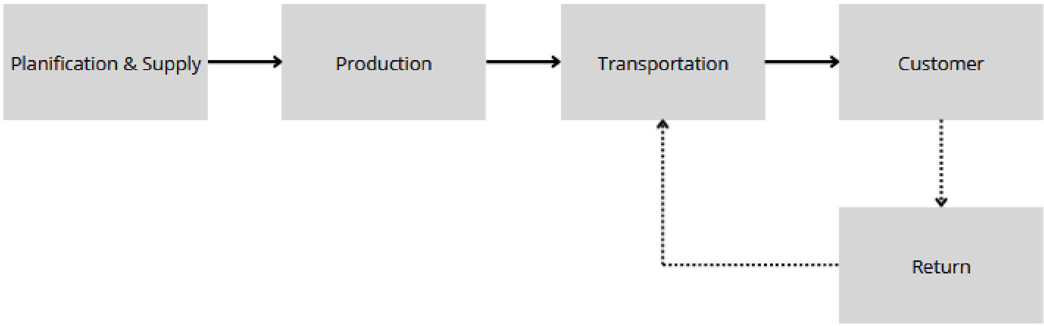

Figure 2. Basic diagram of the supply chain phases. Source: Own work.

- **Planification & Supply**: This phase, **Planification**, involves determining what products or services are needed, in what quantities, and when they are needed. It also involves identifying suppliers, establishing relationships with them, and negotiating prices. The second part, **Supply**, involves acquiring the raw materials, components and other resources necessary to produce the products or services. It also involves managing inventory and ensuring that enough supplies are available when needed.

- **Production:** This part converts raw materials and components into finished products. It also involves managing the production process and ensuring that products are produced efficiently and of the right quality.

- **Transportation:** This phase involves getting the finished products to the customer. It also involves managing the distribution process and ensuring that products are delivered in a timely manner and in good condition.

- **Customer:** The final part of the supply chain. It is the person, company or system that requires that product or service produced. It is the reason why the supply chain exist.

- **Return/Refund:** This phase is basically the return or refund of the money. It happens when the customer is not happy with the performance of the product/service or has any issue and wants the economical refund or substitution. For doing that, the transportation phase is quite important for bringing back the product to the producer.

We have talked about supply chain for products, but supply chain is also for services. The supply chain phases for a service are similar to those for a product, but with some key differences.

- **Planification & Supply:** The service is defined, the target customers are identified and the necessary resources are determined. In the Supply phase, important components for the development of the service are acquired like a team, equipment and supplies.
- **Production:** In this phase, customer service is provided. This phase may be unique for each type of service, but generally involves an interaction between the service provider and the customer.
- **Delivery:** In this phase, the quality of the service provided is evaluated and customer comments are collected.
- **Return:** In this phase, customer complaints are managed and necessary corrections are made.

Supply Chain Management (SCM): The management of the supply chain could be defined as the process of planning, organizing, executing and controlling all activities involved in the movement of a product or service. It has the aim of optimizing the efficiency and profitability of the supply chain. It also guarantees the availability of products at the right time and place and meets the customer needs efficiently.

The **benefits** of good management could be the reduction of cost, a better performance of the service for the customer, and an improvement in the competitiveness and profitability.

2.1.2. Logistics

According to the Real Academia Española, logistics means “Set of means and methods necessary to carry out the organization of a company or a service, especially distribution.” [2] For a close look, we can define logistics as a coordinated process which manages and controls the storage and the delivery of goods in a supply chain. The main aim of the logistics is to manage all the operations related with the movement of raw materials or products as efficiently as possible.

This activity must be carried out in accordance with the agreed level of service and at the lowest possible logistical cost, under just-in-time conditions [3].

A key aspect of logistics is that it acts as a link between the different actors in the supply chain, in order to guarantee that stages such as: supply of raw materials, preparation of orders or ensuring that there are no delays in deliveries [3].

Logistics management is normally involved in this kind of activities: [4]

- Incoming transportation
- The transportation that leaves
- Fleet management
- Storage
- Material handling
- Order fulfillment
- Inventory management
- Demand Planning

- **Logistics vs SCM**

Think of logistics as the bridge connecting various players within the supply chain. It ensures the smooth movement and storage of goods, guaranteeing they reach customers in the right amount, quality, and at the right time. This involves meticulous planning, execution, and control. On the other hand, SCMt encompasses the entire life cycle of a product, from initial contact with suppliers to final delivery to the customer. It is a broader concept, with logistics playing a crucial (arguably the most essential) role in its successful execution [5]. In simpler terms, logistics is the "how" of getting goods to the customer, while SCM is the "what" and "why" behind the entire process.

2.2. Context

During human history, technology and industry experienced some revolutions that made a change in the global economy, the way that we live and the understanding of the world.
With the implementation of new technologies never used before in previous periods, a new revolution has come, the fourth one. It started a few years ago, specifically in the second decade of the XXI century. This concept of new industrial structuring or Industry 4.0 was handled for the first time at the Hannover Messe, one of the world's largest trade fairs dedicated to the topic of industry development, in 2011 [6].

This industrial revolution, called Industry 4.0, according to Klaus Schwab, Founder, Executive Chairman of the World Economic Forum, is led by new technologies such as AI, robotics, the IoT, autonomous vehicles, 3D printing, nanotechnology, biotechnology, materials science, energy storage, and quantum computing [6].

Following what Mr. Schwab says, this new industry has some opportunities and challenges. According to him, it will help with economic growth reducing the transportation and communication cost, logistics will be easier to control, and could make trade easier that could lead to higher global income levels and improved lives for many. To add some more, this new industry could help into the development of new products or services using the IoT or technologies such as Blockchain.

Industry 4.0 is active in many fields, including in the aeronautical sector. Some producers started using the new technologies for the design and production of componentes, spare parts for aircrafts with 3D printing, making simulations for optimizing the design and improving the performance, or using robotics in factories for the automation of repetitive tasks. It is also useful for the maintenance control for airplanes using IoT or the optimization of aircraft performance using big data, (...). Its impact on the Supply Chain could help in solving issues that happen in different areas, for example in the efficiency, flexibility or sustainability of it.

The challenges that could be found, the job displacement of some people caused by automation, increasing the dependence of technology or increasing the risk of cyberattacks or software errors [6].

To summarize, it is quite important to make a study of the impacts in the aeronautical sector because it is a good tool to be competitive, improving the company's efficiency and productivity. It also helps with the innovation for the development of products and services and also helps with one of the most important things, sustainability, implementing technologies such AI or big data could help the company optimizing its resources and reducing carbon emissions.

2.3. Definition and characteristics of Industry 4.0

This concept refers to a new industrial revolution propelled by the new technologies from the present days like the internet, big data, AM, remote connection or cloud computing [7].

It aims to improve productivity, efficiency and flexibility while enabling smarter decision-making and customization in manufacturing and supply chain operations [8]. It is also the interconnection and cooperation of virtual and physical production systems with the product itself. Offers flexibility and the possibility to personalize a product or service for the consumer [7].

Manufacturers are incorporating new technologies into production facilities and throughout their operations, thus, creating smart factories.

These smart factories are equipped with advanced sensors, embedded software and robotics that collect and analyze data, thereby improving decision making. The value increases even more when production operations data is combined with operational data from Enterprise Resource Planning (ERP), supply chain, customer service and other business systems to take visibility and insight to the next level from information that before it was compartmentalized.

Thanks to new technologies, analysis can be carried out on the large amounts of big data collected by sensors equipped in factories, guaranteeing real-time visibility of manufacturing assets and can provide tools to perform predictive maintenance in order to minimize equipment downtime [9].

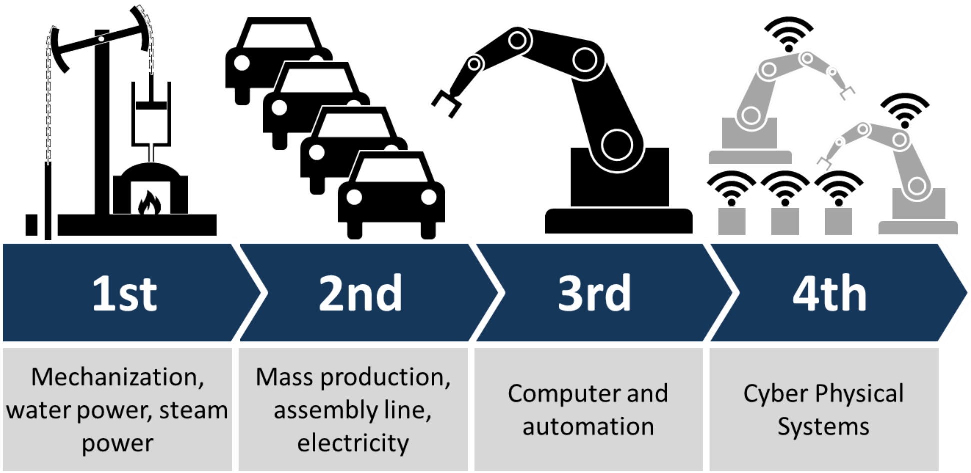

Figure 3. The different industrial revolutions that existed. Source: [10]

2.4. New technologies from Industry 4.0

With the increase in computer use, the use of the Internet and the growth of digitization, enormous contributions have been made to the origin of new technologies, the improvement of existing inventions and the search for new means and methods to optimize processes both in the day to day of a company.

For this reason, it is considered important to mention the new cutting-edge technologies that have come to us in recent years and explain what they are and what impact they can have on the operation of a company.

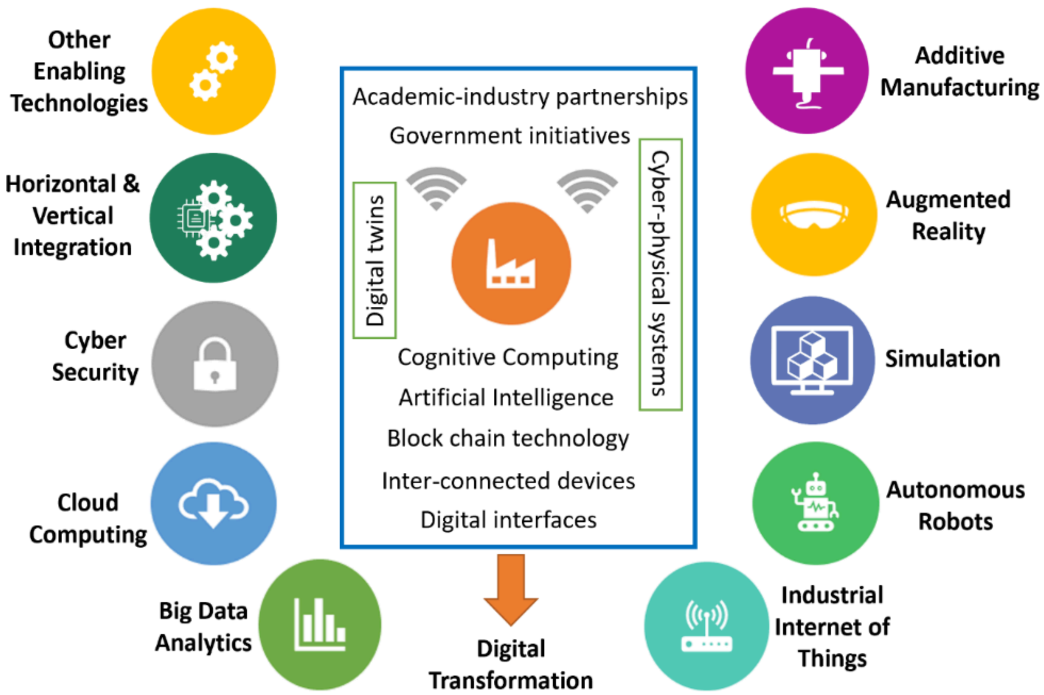

Figure 4. Different Technologies that are typical from Industry 4.0. Source: [11]

2.4.1. Big data

The use of this data in the context of Industry 4.0 allows decision making in real time.

Big data involves the collection and analysis of large volumes of data through specific software. This software has the ability to transform information into actionable and extremely useful data.

The goal of big data is to use this data to:

- **Make predictions:** Allows companies to anticipate trends and make more informed decisions.
- **Monitor productivity:** Helps companies identify areas for improvement and optimize their processes.
- **Improve decision-making:** Provides companies with valuable information to make more strategic decisions in different areas, from operational to organizational and financial.

Big data plays a vital role in the new industry 4.0. This industry is characterized by hyperconnectivity, with hundreds of systems connected to each other. Big data gives much more capacity and utility to other emerging technologies such as IoT and AI. It does this by extracting large volumes of data, organizing it, analyzing it, and converting it into high-value information to achieve operational and productive excellence [12].

According to Jaime Mira Galiana [12], these are the different Big Data Applications.

- **Smart manufacturing processes:** It enables system integration and the creation of "smart factories" with machines that perform complex tasks, solve problems, and make decisions autonomously.

- **Supplier management:** It allows establishing efficient systems to improve the relationship with suppliers, for example, by automatically scheduling orders based on historical analysis.

- **ERP:** Optimizes the company's human and technological resources through a complete and comprehensive vision of processes and systems.

- **Logistics and warehouse optimization:** It allows the creation of "smart warehouses" with automated and robotic systems for repetitive tasks, freeing up operators for supervision and control functions.

- **Predictive maintenance:** Predicts possible failures in machinery before they occur, avoiding production stoppages and economic losses [12].

Industry 4.0 thrives on the power of Big Data. By crunching massive datasets, businesses unlock hidden patterns that fuel predictive analytics. These insights empower machines to operate with precision and autonomy, driving a new era of intelligent manufacturing. Big Data serves as the ultimate compass for strategic decision-making, guiding businesses towards optimal outcomes. Without this data-driven approach, Industry 4.0's progress and very existence would be unimaginable.

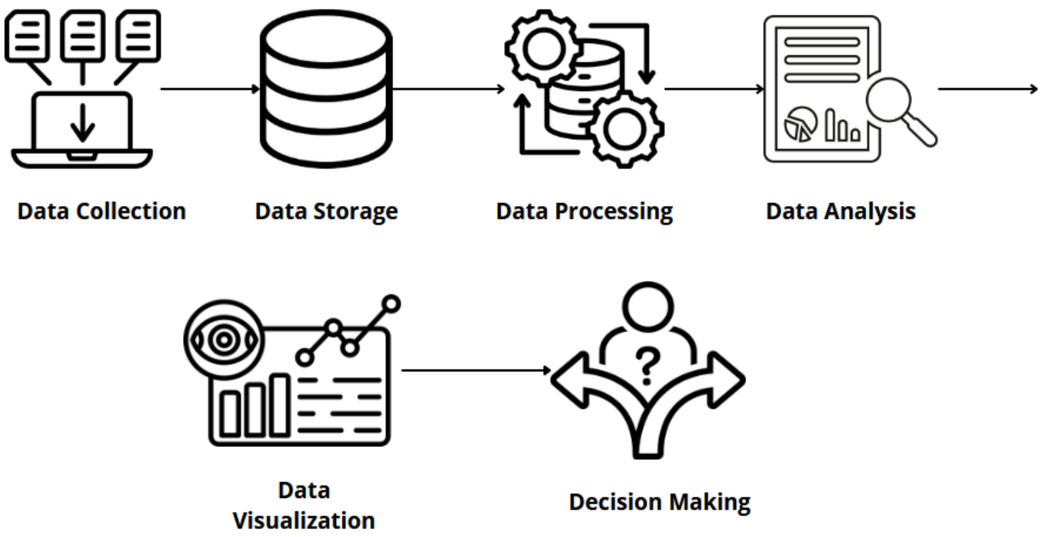

Figure 5. Basic diagram of Big Data phases. Source: Own work.

1. **Data Collection**:
   - Gathering data from various sources, which can be structured, semi-structured, or unstructured.
   - **Data Sources**: Sensors, IoT devices, business transactions, server logs, (...).
2. **Data Storage**:
   - Storing the data in systems capable of handling large volumes.
   - **Technologies**: NoSQL databases, Amazon S3, (...).
3. **Data Processing**:
   - Organizing and preparing the data for analysis. This process may involve data cleaning, transformation, and aggregation.
4. **Data Analysis**:
   - Applying analytical techniques and algorithms to extract meaningful information and patterns from the data.

- **Methods**: Descriptive, predictive, prescriptive analysis, data mining, Machine Learning (ML).

5. **Data Visualization**:
    - Representing the analysis results graphically to facilitate understanding and decision-making.
6. **Decision Making**:
    - Using the obtained information to make strategic and operational decisions.
    - **Impact**: Improved efficiency, process optimization, development of new products and services, (...).

2.4.2. Data Science

Data Science is another relevant topic that is gaining some importance inside companies in the present days. Data science consists in analysis and the study of data for the extraction of vital information for companies. It has a multidisciplinary approach that involves fields like mathematics, statistics and artificial intelligence for the analysis of a big quantity of data.

It has gained importance because of the increasing quantity of data generated nowadays, the technological advances, the necessity of information and knowledge for decision making, among others.

According to Amazon Web Services, the process of Data Science is divided into the following parts [13].

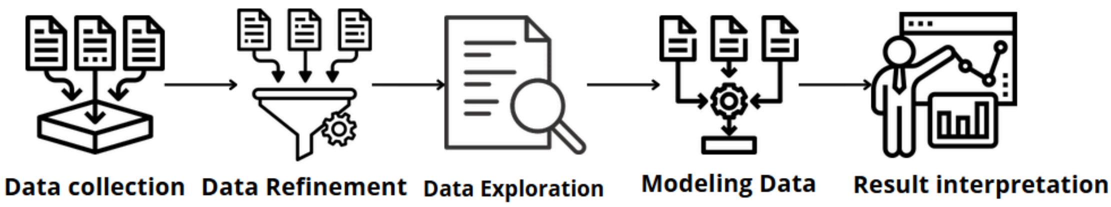

Figure 6. Basic diagram of the Data Science phases. Source: Own work.

Data Collection: Collection of the data from internal or external databases, from CRM of the company, web server registers, social media or data collected from third companies.

Data Refinement: is the process of normalizing and cleaning data for analysis. Brief examples:

- **Handling missing data:** Filling in missing information in an accurate and consistent manner.
- **Correcting errors:** Removing typos, inconsistencies, and incorrect values.
- **Removing outliers:** Identifying and removing values that do not fit the normal distribution.

Data Exploration: Data exploration is a preliminary analysis of data that is used to plan further modeling strategies. Is a crucial step in the data analysis process because it allows data scientists to formulate hypotheses, select variables and choose the right model.

Modeling Data: Data scientists use ML software and algorithms to extract deeper insights from data, predict outcomes, and prescribe the best course of action. Which process involves training a model, evaluating the model and tuning the model (the model is adjusted and optimized multiple times to improve accuracy and performance).

Result Interpretation: With the final data, scientists and analysts convert the information in action. They create diagrams, graphics and tables to represent tendencies and predictions.

Uses

- **Decision Making:** It permits us to analyze some tendencies and relations not visible in a simple way. Which companies can take strategic decisions with a lot of information and based on specific facts and not only intuition.
- **Process optimization:** We can analyze the associated data with a process to encounter areas of inefficiency or bottlenecks. This permits an optimisation process, costs reductions or improving the general development.
- **Predictive analysis:** Can be used for developing predictive models for future events with an accuracy grade. Example: Predict the demand for a product, the fraud risk in a financial transaction or the probability of a client to leave a service.
- **Development of new products:** Analyzing customer and market data, can help identify unresolved needs or problems. Based on this information, new products and services can be developed that meet those needs and have a greater chance of success.

2.4.3. Artificial Intelligence

Asking an AI about its definition, it provides the following result. “AI is a field of computer science that seeks to create machines that can perform tasks that normally require human intelligence, such as learning, reasoning, and perception” (Google Gemini, 2024).

AI in aviation has been employed in air combat, the aeronautical industry, cognitive systems, aircraft maintenance repair, data analysis, defect detection, and deep learning in defect detection.

Also supports the detection and resolution of onboard problems during flight, reducing the risk of falls and accidents by influencing the predictive stability behavior of aircraft. In addition, implementing advanced monitoring and tracking systems, such as predictive maintenance, allows airlines to identify and fix logistical issues before they cause flight disruptions

2.4.4. Industrial Internet of Things (IIoT)

New technologies have allowed us to provide physical objects with real communication potential. When given to machines, this new-found communication allows them to interact with each other or directly with the products, but also to decentralize decision making, generating responses in real time [7].

The IIoT is a network of sensors, instruments, and autonomous devices in the industry that connects to the Internet to:

- **Collect data:** Real-time information about operations.
- **Perform analysis:** Obtain information about the status of equipment, the efficiency of processes, and the quality of products.
- **Optimize production:** Improve efficiency, reduce costs, and increase quality.

It is mainly used in:

- **Manufacturing:** Machinery monitoring, quality control, predictive maintenance, process automation.

- **Transportation:** Route optimization, shipment tracking, fleet management, road safety.
- **Energy:** Network monitoring, demand management, renewable energy generation, energy efficiency.

Examples of application of the IIoT:

- **Optimization of machine performance:** Maximize uptime.
- **Use of autonomous vehicles:** Transport of components and products.
- **Reduction of human errors:** Connected tools to save time and prevent errors.
- **Improvement of logistics and distribution:** Real-time data on the location and condition of products.
- **Reduction in the number of accidents:** Wearables that collect data from the operator to reduce the possibility of accidents.

The main difference between the IIoT and the "normal" one is that the first one is focused on the industry and the other one for consumers.

Figure 7. Opportunities for Industrial Internet of Things. Source: [11]

2.4.5. Blockchain

Blockchain is a framework which consists of a set of private distributed ledgers and a single public ledger arranged in blocks. Each private ledger allows the private sharing of custody events among the trading partners in a given shipment. Privacy is necessary, for example, when trading high end products of chemical and pharmaceutical products [14].

The second type of ledger is a type of blockchain public ledger. It consists of the hash code of each private event in addition to monitoring events. The latter provides an independently validated immutable record of the pseudo real-time geolocation status of the shipment from a large number of sources using commuters-sourcing (Wu et al. 2017, Michael D. Santonino III. 2018).
Also exists a third type which is a hybrid one that combines both functionalities of the two Blockchain types.

Blockchain has some benefits, which could be the following ones:

- Improve the safety
- More transparency
- Cost reduction
- Efficiency improvements

Example of uses in avionics:

- IATA is developing a new load track system using Blockchain technology.
- Lufthansa is using Blockchain to create a digital register for aircraft maintenance [14].

2.4.6. Additive manufacturing

3D Printing or AM is a technology that consists in the production of three-dimensional objects from a digital model created on a computer. It basically works by depositing layers of material one on top of the other until the desired shape is achieved. 3D printing does not remove material, but rather adds it.

Objects created by AM can have different sizes, can be compounded by various shapes and also it can be made with different materials like plastic, ceramic or metals [15].

3D Printing is useful because it is customizable, it allows for the creation of unique and personalized objects from digital designs. It is efficient because it reduces the material waste and allows for part design optimization and it is starting to be accessible for a lot of people because the price of some printers, software and materials are dropping now. Also it is cheaper and more sustainable [15].

It has plenty of applications in a wide range of areas, such as:

- Prototyping ⇒ Creation of cheap prototypes to test designs before mass production.
- Manufacturing ⇒ Used to manufacture custom and personalized parts.
- Medicine ⇒ Prosthetics, implants, and anatomical models.
- Others.

2.4.7. Autonomous Robots

Robots are becoming increasingly autonomous, flexible, communicative and cooperative. By interacting with their environment and products and as they learn from humans, they will provide the industry with a broader range of capabilities [7].

They can navigate and operate without human intervention. They are powered by AI and ML, which enable them to perceive their surroundings, make decisions, and perform tasks autonomously [16].

Applications:

- **Manufacturing:** Transport materials, assemble products, and perform other tasks on factory floors.
- **Logistics:** Used to move goods and products in warehouses and distribution centers.
- **Healthcare:** Used to deliver medications, transport patients, and perform other tasks in hospitals and healthcare facilities
- **Retail:** Used to stock shelves, assist customers, and perform other tasks in retail stores.
- **Agriculture:** Used to plant and harvest crops, tend to livestock, and perform other tasks on farms.

Benefits

- Increased productivity ⇒ Robots can work 24/7 and can perform tasks faster and more accurately than humans.
- Improved security ⇒ Can work in hazardous environments that are unsafe for humans.
- Costs reduction
- Greater flexibility ⇒ Robots can be reprogrammed to perform new tasks.

2.4.8. Cloud Computing

The communication and the exchange of information have been made easy thanks to Cloud technology, which provides access to network connection [7].

As performance has become increasingly impressive and reaction time gone down to only a few milliseconds, production machinery data and function will be available anywhere and from any terminal, all thanks to the Cloud [7].

It plays a crucial role in Industry 4.0 by providing a scalable and flexible infrastructure for storing, processing, and analyzing vast amounts of data generated by sensors, machines, and IoT devices in real time. This enables companies to leverage this computing technology to enhance their manufacturing operations, efficiency, productivity, and adaptability in an increasingly automated and connected industrial environment [17].

Types of Cloud Computing [17]:

- **Public Cloud:** Public clouds utilize external service providers and are owned and managed by companies that allow users to access resources on demand in a shared manner.

- **Private Cloud:** Private clouds are owned by a single organization and are located on their own premises. This cloud model provides greater control over services and data management. Additionally, automated private cloud management makes it a highly beneficial option.

- **Hybrid Cloud:** Hybrid clouds combine the foundation of a private cloud with the strategic use and integration of public cloud services. In this way, service providers can leverage the advantages of both models, namely: the services of the public cloud and the greater control and security of the private cloud. This type also has another advantage, which is the ease of porting data, applications, and other services.

Cloud Computing Services in Industry 4.0 [17]:

- **Infrastructure as a Service (IaaS):** Provides access to IT infrastructure services. Businesses pay to access IT infrastructure, such as: servers, virtual machines, storage, operating systems...

- **Platform as a Service (PaaS):** It is the tool that enables the creation of applications in the cloud. The available hardware and software resources facilitate the creation of these services.

- **Software as a Service (SaaS):** It is the most popular application of cloud computing services. It provides access to complete software applications through a browser or program interface. It integrates global services such as the infrastructure, maintenance, and updates of the application software.

Advantages [17]:

- **Higher profitability:** Thanks to cloud computing, costs are reduced because the availability of these resources allows both the elimination of the expense of acquiring software or hardware and the management and maintenance of the same.

- **Greater flexibility:** Remote access to computing services gives users more capacity to make use of these resources simply with an internet connection.

- **Greater security:** Cloud providers apply highly sophisticated security mechanisms, which guarantees that cloud computing is a solid and secure technology that protects data, applications, and other virtual infrastructure from the risks present in the computational system.

- **Greater efficiency:** Thanks to the providers, the best IT advances and the latest updates are available, which the companies using these resources can benefit from, improving their productivity and performance. Also it has quick access to the real time information.

2.4.9. Cyber security

In order to ensure the development of Industry 4.0 and the interconnection of systems, it is essential to secure a large amount of communication channels without performance [7]. Cybercriminals are constantly evolving their tactics and exploiting vulnerabilities to gain access to sensitive data, disrupt operations, and extort businesses.

There are some common threats that digitized companies could face in the future, like malware, phishing attacks, denial of service, (...). That's why some companies have to be ready to protect their company from this kind of attacks, especially companies that use the internet, cloud computing or some kind of software connected online.

Benefits of Cyber Security in Industry 4.0 [18]:

- **Enhanced Efficiency and Decision-Making:**
    - **Streamlined Operations:** Secure systems minimize disruptions, allowing for smooth and efficient processes.

    - **Informed Decisions:** Timely access to accurate and protected data empowers better decision-making.

- **Boosted Customer Trust and Loyalty:**
    - **Data Protection:** Safeguarding customer information fosters trust and confidence in the company.

    - **Secure Transactions:** Protected transactions instill a sense of security and reliability among customers.

- **Reduced Costs and Risk Mitigation:**
    - **Attack Prevention:** Proactive cybersecurity measures minimize the likelihood of costly cyberattacks.

- **Incident Mitigation:** Reduced downtime, data recovery expenses, and reputational damage.

- **Prevention over Reaction:** Prevention is always more cost-effective than dealing with the aftermath of an attack.

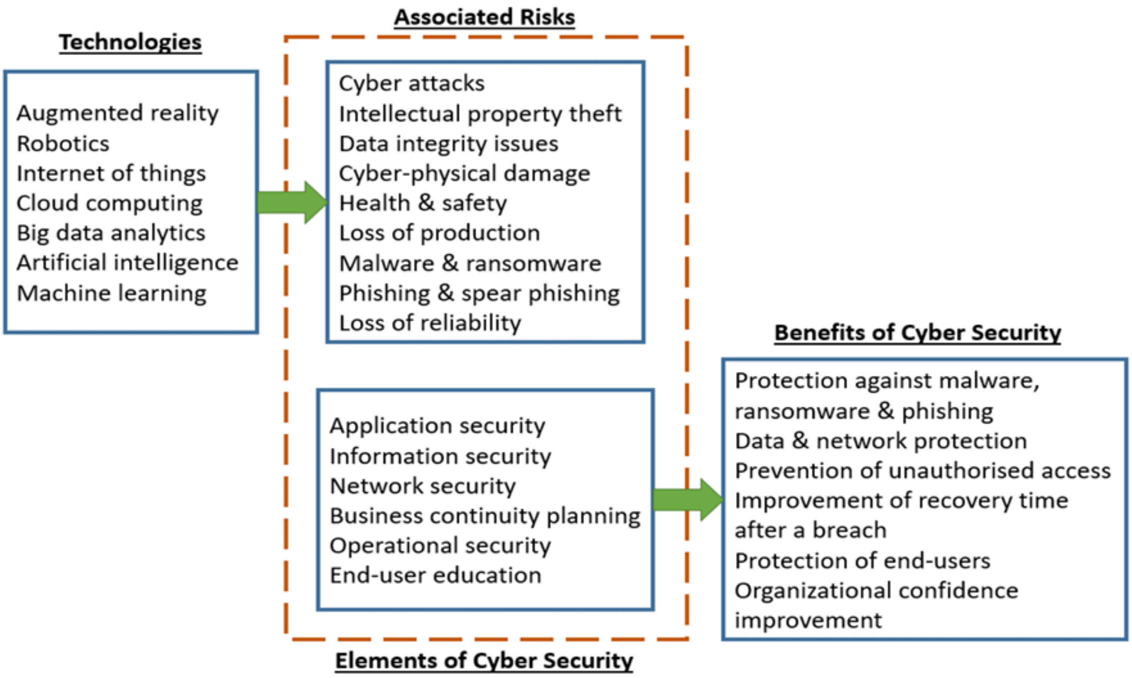

Figure 8. Overview of Cyber Security. Source: [11]

2.4.10. Augmented Reality and Virtual Reality

Nowadays systems based in Augmented Reality (AR) are quite basic and underdeveloped but in the future it will help to give real time information to improve the decision making and the work procedures [19].

The data availability in an integrated system provides users with new ways of accessing information. Today, we see a surge in the use of virtual and AR technologies, such as the glasses used in manufacturing procedures, which allow wearers to visualize an environment by superimposing real and simulated objects, improving creation, manufacture and reparation procedures [7].

Virtual reality (VR) is a technology that creates fully immersive, simulated environments. Meanwhile, AR overlays digital information onto the real world.

Applications of VR and AR in Industry 4.0:

- **Design Optimization:** VR allows engineers to create and interact with 3D models of products and facilities, enabling them to optimize designs and identify potential issues before physical prototypes are created.

- **Plant Maintenance and Control:** AR can overlay digital information onto real-world machinery, providing workers with real-time instructions and guidance for maintenance tasks.

- **Operator Training and Education:** VR can create immersive training simulations, allowing workers to practice procedures and learn new skills in a safe and controlled environment.

- **Incident Assistance and Resolution:** AR can facilitate remote collaboration between experts and on-site workers, enabling real-time problem-solving and incident resolution.

Benefits of Using VR and AR in Industry 4.0:

The adoption of VR and AR in Industry 4.0 brings about several benefits for businesses, including:

- **Process Improvement:** VR and AR can streamline processes, reduce errors, and improve overall efficiency.

- **Reduced Downtime:** VR-based training can shorten training time, while AR-guided maintenance can minimize downtime.

- **Enhanced Safety:** VR can provide workers with safe training environments, while AR can highlight hazards and provide safety warnings.

- **Cost Savings:** VR and AR can reduce costs associated with training, travel, and physical prototypes.

2.4.11. Simulation

Using data in real time, simulation allows us to virtually model our physical environment with machines, products and even humans. This allows operators to test and optimize processes and operations, decrease machine adjustment time and improve quality [1], [7].

Also allows to [20]:

- **Evaluate different scenarios** before implementing changes in the physical plant.
- **Reduce costs** by preventing errors and improving efficiency.
- **Improve decision-making** by having a better understanding of how changes will work.
- **Increase productivity** by optimizing processes.
- **Train employees** in a safe and controlled environment.

Simulation is a crucial tool for Industry 4.0 because it is more agile and adapts to market changes. Make better data-driven decisions and reduce the risk of costly errors. It is also a good tool for innovation and development of new products and processes [20].

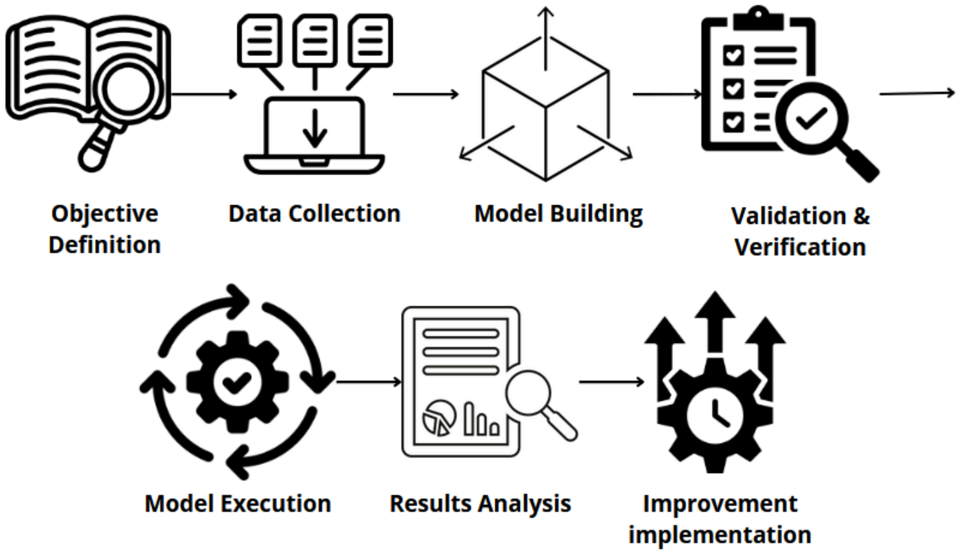

Figure 9. Basic diagram of the Simulation phases. Source: Own work.

1. **Objective Definition**
    - Establish the goals and scope of the simulation. Define what is expected to be achieved and the specific problems to be addressed.
    - **Examples**: Process optimization, cost reduction, quality improvement, design validation.
2. **Data Collection**
    - Gather the necessary data to build the simulation model. These data can come from sensors, historical records, databases, among others.
3. **Model Building**
    - Create a digital model of the system or process to be simulated. This model should accurately represent the real behavior of the system.
4. **Validation and Verification**
    - Ensure that the simulation model is an accurate representation of the real system and functions correctly.
    - Compare model results with historical data, perform consistency and coherence tests.
5. **Simulation Execution**
    - Run the simulation model to analyze different scenarios and operating conditions.

- Perform multiple simulation runs, vary parameters and input conditions, collect results.

6. **Results Analysis**
    - Evaluate the simulation results to gain insights and make informed decisions.
    - **Methods:** Statistical analysis, charts and visualizations, scenario comparisons.
7. **Implementation of Improvements**
    - Apply the improvements and recommendations obtained from the simulation analysis to the real system.
    - Process adjustments, planning changes, implementation of new technologies.

2.4.12. Horizontal and vertical system integration

Today, businesses, suppliers and consumers are rarely connected, and the same goes for different departments within one company. With Industry 4.0, the exchange of data develops cohesion (regarding products and production) between these different partners [7].

Horizontal Integration

- **Focus:** Connects machines, equipment, and production units within the factory floor. Focusing on connecting resources and information networks within the value chain. It facilitates seamless cooperation between companies, enabling real-time product and service delivery.
- **Benefits**
    - Streamlined communication and data sharing across different machinery.
    - Enhanced collaboration between robots and other automated systems.
    - Improved overall production flow and efficiency.
    - Enables real-time monitoring and control of production processes.

Vertical Integration

- **Focus:** Connects the factory floor with higher organizational levels, including ERP systems, customer relationship management (CRM) systems, and other business functions.
- **Benefits**
    - Improved visibility and control over the entire supply chain.
    - Data-driven decision making based on real-time production data and customer insights.
    - More agile and responsive production planning based on market demands.
    - Enables predictive maintenance by analyzing sensor data to anticipate equipment failures.

These integrations are important for Industry 4.0 because they create a connected manufacturing web which eliminates communication silos and fosters a more efficient and responsive production flow (horizontal integration) and allows for data-driven decision making and better coordination across the entire value chain (vertical integration).

There are other technologies related to Industry 4.0, but according to some sources, these ones are the closest to the aeronautical field.

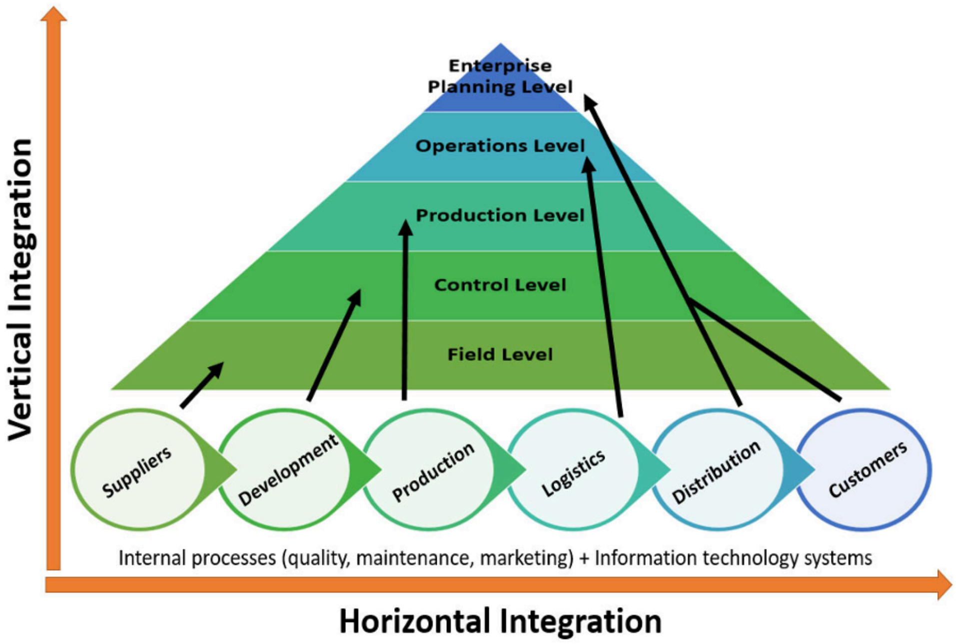

Figure 10. Horizontal and vertical integration models. Source: [11]

2.5. Impact in the sector, economics and sustainability

Industry 4.0 is improving the growth and the development of the aeronautical sector due to the improvements in design, production, digitalization, personalization and logistics management. For example, aerospace companies are already using 3D printing to apply for new designs that reduce aircraft weight by reducing their spending on raw materials such as titanium [21].

Industry 4.0 enables continuous resource productivity and efficiency gains to be delivered across the entire value network. It allows work to be organized in a way that takes demographic change and social factors into account. According to Eduardo Cardoso Moraes, “A flexible work organization will enable workers to combine their work, private lives and continuing professional development more effectively, promoting a better work-life balance”. He adds that “This change is already impacting the industrial area, especially in areas where the product life cycle is small and a constant search for improvement is needed, such as the electronics, automotive and aviation sectors” [21].

In terms of economic growth, it is expected that AI could contribute up to $15.7 trillion to the global economy in 2030, of this, $6.6 trillion is likely to come from increased productivity and $9.1 trillion is likely to come from consumption-side effects and also labour productivity improvements are expected to account for over 55% of all GDP gains from AI over the period 2017-2030 [22] .

IoT and digital manufacturing lead to “Productivity improvements such as lower maintenance costs (up to 60%), or lower capital appropriations (25%). New operational processes resulting in lower labor cost (30%) with improved OEE2 (5%-10%) and reduced scrap levels (30%-50%). According to Vyshnevskyi et al. “The implementation of Industry 4.0 and AI should ensure substantial economic growth”, but they add that it is not the same boom as the industrialization of the 60s of the last century. Digitalization of the global economy cannot provide as high growth as half a century ago, but probably will give economic growth in the future [22].

Nowadays, the implementation of Industry 4.0 doesn’t show a correlation between the growth of the economy and the processes implemented with AI. Only one country in 2018 that appears in the top 10 countries in the top of World Information and Communications Technologies (ICT) Development Index, has a GDP growth rate more than the world average. In a hypothetical scenario where Industry 4.0 and AI really have an impact on the present economy all the top 10 countries should be above the average which is not the case at the moment [22].

To conclude, Industry 4.0 is not yet the key driver of economic development in this historical period the economic efficiency of Industry 4.0 and AI for individual industries or enterprises is not questioned, but the individual positive results did not become universal due to objective circumstances and require further research in this direction.

For the sustainability aspect of Industry 4.0, there is still a high consumption of resources, raw materials, information, and energy, which is environmentally unsustainable despite numerous advantages of Industry 4.0 and this has made society and the public sector more aware and concerned about the risks and environmental challenges [23].

This present industrial revolution has focused more on production and not on an environmentally sustainable framework, but with Industry 4.0 modern technology will create greater sustainability and increase the quality of products. Some studies explain that Industry 4.0 has tremendous opportunities to achieve this sustainability and also showed the benefits of adopting technology in manufacturing (such as 3D printing) for environmental sustainability [23]. The problems associated with this industry in terms of environmental sustainability have not been adequately explored because these are still new technologies. There is a high level of consumption and use of raw materials and energy. The environment is on the receiving end where waste is concerned. Recycling must take place, and therefore, to avoid a negative environmental impact, recycling is highly encouraged, and more energy-saving will be achieved.

Industry 4.0 is expected to give some improvements for the following years using its technologies, here are some scenarios. To get better energy efficiency, there are some benefits of adopting and integrating the IoT with Industry 4.0 in the manufacturing sector, software tools can be optimized, which means a 30% reduction in energy consumption [23]. Intelligent optimization algorithms are used to optimize energy consumption to save energy in production and management through the data processes platform are used to optimize energy consumption to save energy in production and management through the data processes platform.

To save on the use of materials, technologies like AM will help because it is effective and more efficient and is less wasteful of resources than conventional subtractive methods, the present processes are still inefficient on the energy usage but have a positive impact on maintenance and logistics. Another technology such a Big data analysis could extend the useful life of the machinery and reduce waste by using preventive and predictive maintenance also using the algorithms and data analysis that was provided to optimize energy use, but still, the main challenge is consumption, which should be solved to reach environmental sustainability. The integration of Industry 4.0 with blockchain technology may allow a redesign of business models among industries by keeping and creating records and implementing contracts. Clean energy and this can be also integrated with Industry 4.0 during the production stage as well as during transportation of the goods to the final consumer [23].

Industry 4.0 presents a double-edged sword for sustainability. While the potential for improved efficiency and reduced waste exists through technologies like 3D printing and big data analysis, current practices still rely heavily on resource consumption. Moving forward, Industry 4.0's success in achieving sustainability hinges on addressing this core challenge and integrating environmentally friendly solutions like clean energy throughout the production chain.

3. Additive Manufacturing (AM)

Without a doubt, the new technologies that are beginning to be installed in our society or that are gaining more and more strength are being of vital help for the progress of the companies that are implementing them in their production processes with the aim of, for example, optimizing processes, and in a certain way achieving an improvement in environmental sustainability through the proper application of technologies for the uses that companies give them.

These new advances that come hand in hand with a new industrial revolution have helped companies in different industrial sectors such as aeronautical/aerospace, nautical or automotive, among others.

One of the technologies that several companies are using to test prototypes or produce components for their products and that is located within this group of technologies, where Big Data or AI can be highlighted, is 3D printing or also known as AM.

In short, this technology, introduced previously, is being used by multiple companies for the production of prototypes, production of new parts or spare parts for discontinued components. It is a technology that offers various advantages such as having a more agile supply chain, more decentralized and customizable production or a reduction in production costs. It allows the creation of complex, lightweight and resistant parts with unparalleled precision, which opens up a range of new possibilities for the design and manufacture of aircraft.

The different types of 3D printing that are applied in production, the materials that are used and a literature review on AM will be explained in the following point.

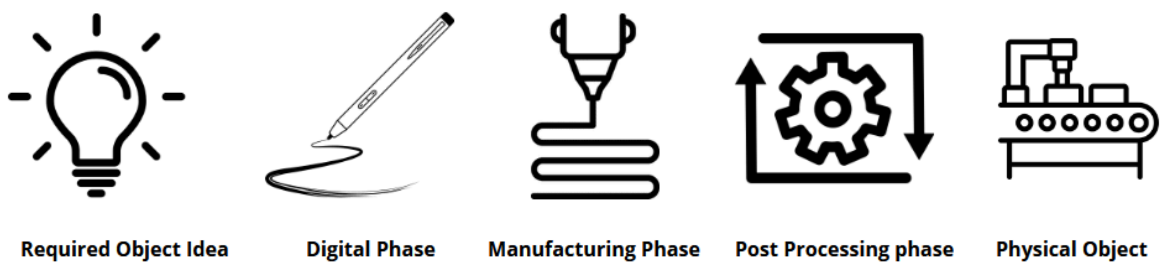

Figure 11. AM processes. Source: Own work.

3.1. Types of AM in aerospace and aeronautics

The aeronautical and aerospace industry are undergoing a radical transformation thanks to **3D Printing**. 3D Printing uses AM rather than the conventional process such as cutting, filling or milling for the production of a final product. The machines create objects from glass, metal, plastic, ceramic or even biological materials (for other fields) using fusers or lasers [23].

According to a study done by the SAP company in 2015, there are several technologies for 3D Printing, the most common technologies are the following [23]:

- Fused Deposition Modeling (FDM)
- Selective Laser Sintering (SLS)
- Stereolithography (SLA)

The first one, **FDM**, deploys a fuser to melt a plastic filament which is extruded through a nozzle and applied layer by layer to build the final product [23].

SLS uses a laser to sinter or melt successively applied layers of powdered build material. When a layer cools and solidifies, a new layer of powder is applied to build up the part.

- **Build material**: Include metals (aluminum, titanium…), glass, plastic and ceramic [30].
- Exists a variation called **Direct Metal Laser Sintering (DMLS)**
    - DMLS and SLS are basically the same process but they have some differences. SLS is used to produce parts using materials like plastics, ceramics and metals, while DMLS is only used to produce metal alloy parts [24].

SLA consists of an ultraviolet light guided by a set of mirrors and lenses that traces the shape and hardens each layer to cure a liquid, photoactive polymer resin material and build the final product [23].

The reality is that there are not only these three types of technologies, there are more of them which are used in other fields like aerospace.

In the following diagram, we can see the different AM processes applied in 3D Printing.

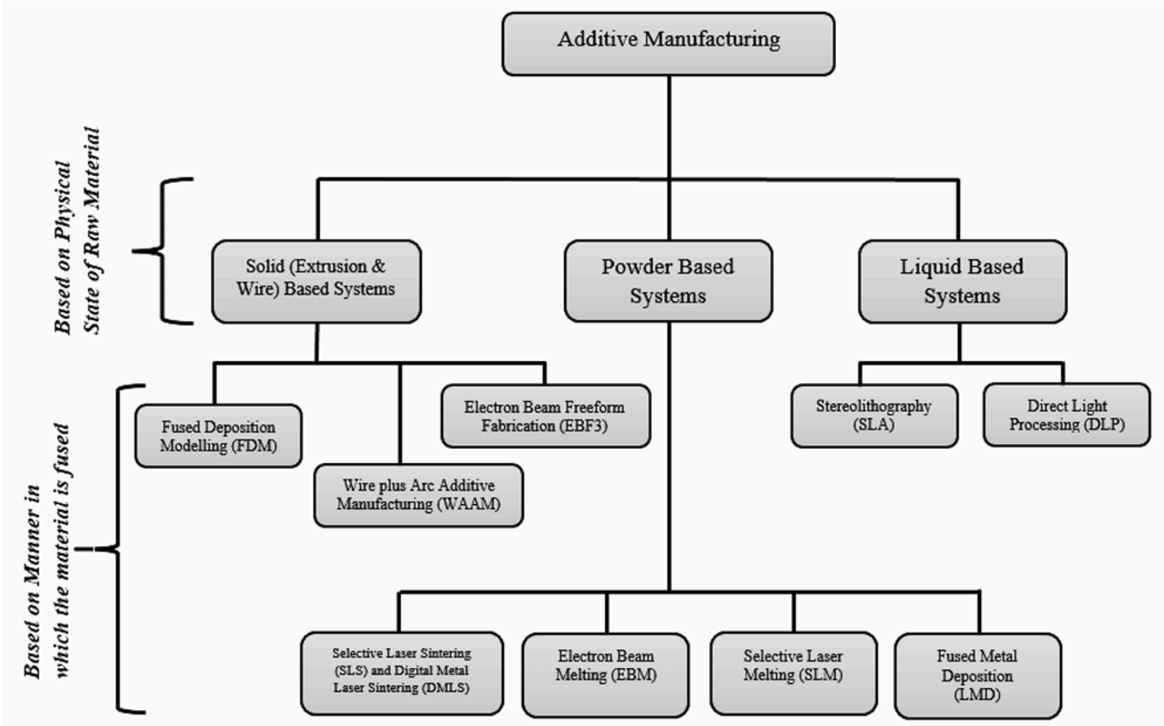

Figure 12. Classification of the different AM Processes. Source: [24]

It is important to know that AM processes can be divided in two different classes:

- Physical State of Raw Materials: Liquid, solid.
- Powder Based Processes: Thermal, ultraviolet light, laser or electrons beam [24].

By looking at the different processes that appear above, we can see the different types of AM. Out of all of these, Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Laser Metal Deposition (LMD) and Wire and Arc Additive Manufacturing (WAAM) are some of the processes that meet the aerospace industry [24].

These processes can produce extremely dense components without any post-processing with comparable mechanical and electrochemical properties to other conventional manufacturing methods [24].

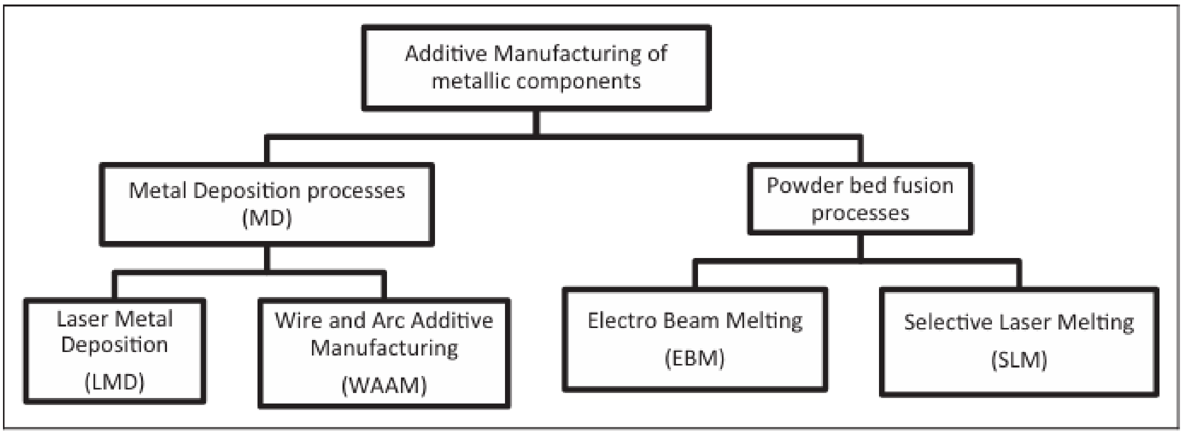

Figure 13. Different AM processes for metals. Source: [25]

Electron Beam Melting (EBM)

Uses a high-energy electron beam to heat and melt the metal powder. The electron beam is generated and then accelerated in a heated filament with a voltage difference of around 60,000 V. Electrons move close to the speed of light and the process has to be carried out in a vacuum, so that electrons do not interact with the atoms of the atmosphere and are not reflected. The beam is focused with a focus coiling in order to achieve the correct spot diameter and electromagnetically positioned with deflection coils that control x–y motion. The building direction (z axis) is denoted by the arrow [25].

- Benefits
    - This system is typically more efficient than a laser beam generator because most of the energy is converted into the electron beam and higher beam energies are available with less cost.
    - Can be used with a wider variety of materials
- Challenges
    - Machine cost are high
    - Build size and constraints in the volume
    - Post processing requirements that could be really

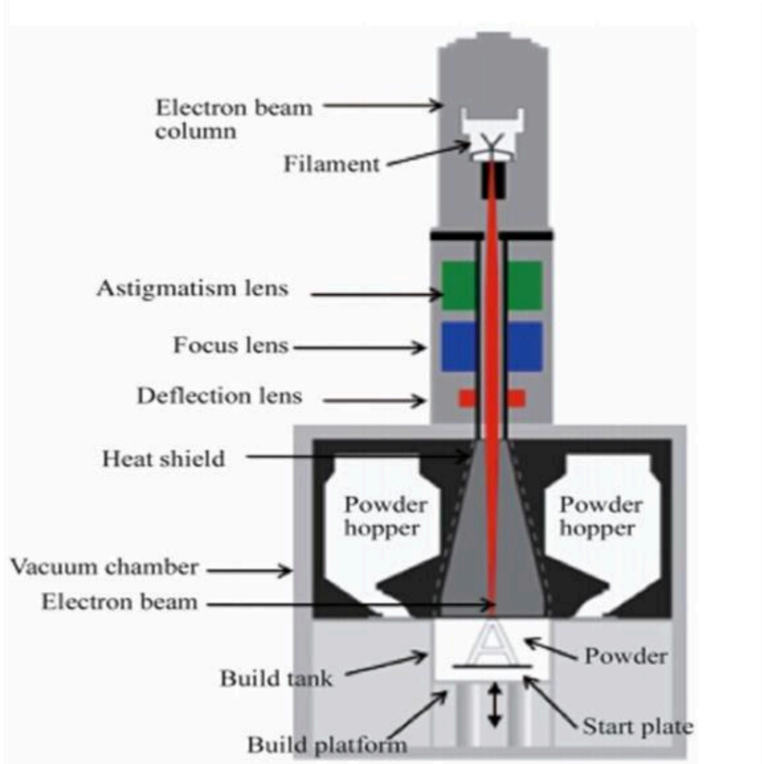

Figure 14. The EBM Process. Source: [26]

Selective Laser Melting (SLM)

As EBM, it also uses a high-energy beam to heat and melt the metal powder (layers 0.1mm thick) which has been racked across the build area using a counter-rotating powder leveling roller. The powder is fed from a container. After finishing a layer, the build platform is lowered by one layer thickness and a new powder bed is spread. This technology uses galvanometers (mirrors) to control the position of the laser spot [25].

- Benefits
    - **SLM** can be used to manufacture with any material.
    - **Material Variety:** Compatible with a wide range of metallic materials.
    - **Low Porosity**
    - Ideal for producing customized parts without the need for specific tooling.
- Challenges
    - High cost
    - Limited Build Size

- Cooling requirements and extensive post-processing

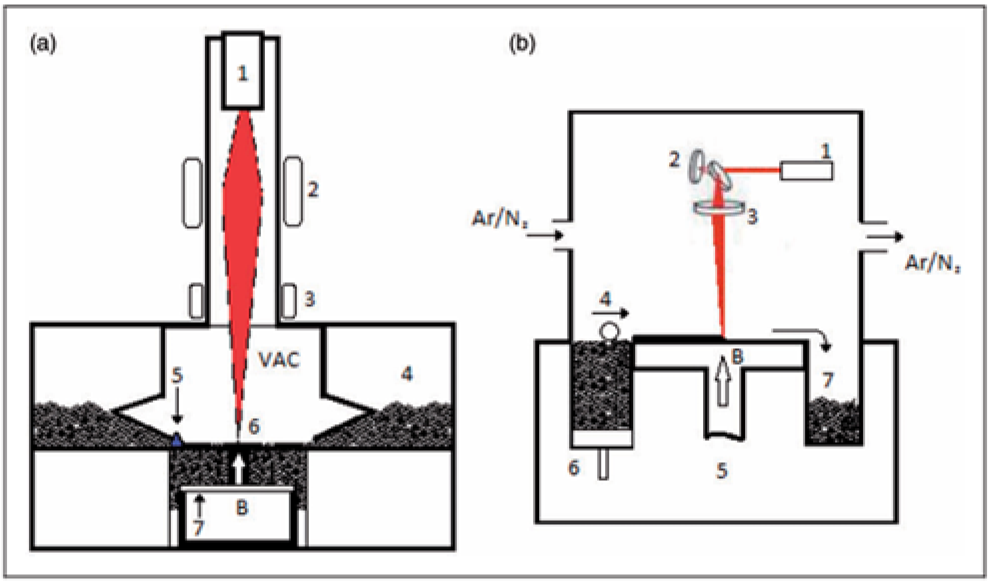

Figure 15. EBM (a) and SLM (b). Source: [25]

Electron vs Laser Beam Melting

Both systems create a powder bed by raking or rolling powder from cassettes into a compacted layer. Whilst in SLM the energy of the photons is absorbed by the powder particles, in EBM the electrons transfer their kinetic energy to the powder particles.

EBM can only process materials like metals, whereas **SLM** can process any material that can absorb energy from a laser wavelength.

Energy cost is an important issue. In **EBM**, most of the energy applied to generate the beam is converted into the electron's kinetic energy but in **SLM**, only 10–20% of the total energy input is converted into the laser beam [25].

In **EBM** and **SLM**, the powder bed is maintained at an elevated temperature. Pre-heating the powder is necessary to minimize the laser/electron beam power requirements and to prevent the part from warping due to high thermal gradient [25].

The difference here is the temperature of both processes.

- **SLM:** Infrared heaters placed above the build chamber maintain the temperature of the powder bed around 90 ºC
- **EBM:** Defocusing the electron beam and scanning the powder bed very quickly over the total surface heats the powder bed before placing the next layer to a uniform pre-set temperature.

Wire and Arc Additive Manufacturing (WAAM)

WAAM can produce vertical, horizontal and angled walls, mixed-material conic sections, enclosed sections, crossovers and intersections. Since this process is not constrained in a cabinet, larger components can be produced.

The products created by WAAM are extremely high quality and are even better than those produced by normal welding procedures [24].

- Benefits
  - **Cost Reduction:** More economical compared to the metal powder used in other AM technologies.
  - **Material Variety:** Compatible with a wide range of metallic materials.
  - **Less Waste:** Generates less material waste compared to traditional manufacturing methods.
- Challenges
  - **Surface Finish:** The quality of the surface finish can be inferior, requiring additional post-processing.
  - **Quality Control:** Ensuring uniform and consistent quality throughout the part can be difficult due to variations in the welding process.
  - **Thermal Distortion:** Heat buildup during the process can cause thermal distortion in large parts.

Electron Beam Freeform Fabrication (EBF3)

Uses an electron beam with a wire based system to fuse metals instead of powders. It can be used to produce structures with materials such as aluminum, high strength steels, titanium, nickel-base alloys and metal matrix composites [27].

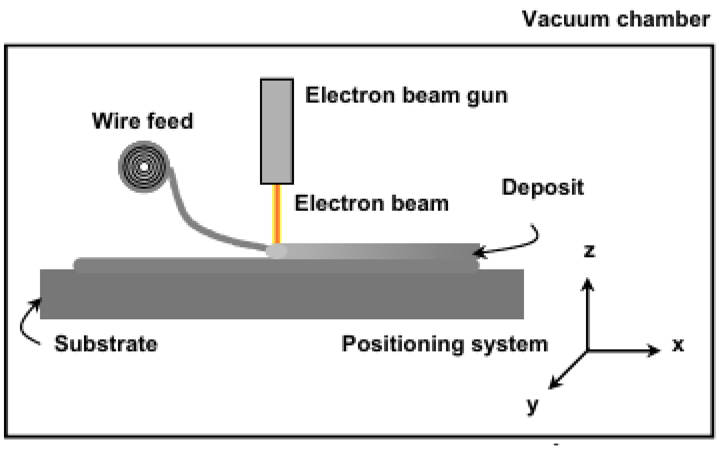

Figure 16. EBF3 illustration. Source: [27]

- Benefits
    - High Precision
    - Rapid construction
    - Fewer defects
    - Oxidation is reduced and the quality is improved because the process is carried out in a vacuum.
- Challenges
    - Cost
    - Operational Complexity
    - Material Limitations

Metal Deposition Process (MD)

In this process, Raw materials are melted and deposited in the form of a powder or wire feedstock. Use as a heat source an electron beam or a plasma source instead of a laser beam as a heat source.

MD processes involve deposition, melting and solidification of raw material in a moving melt pool. The typical microstructure attained is similar to that in the SLM process due to the high cooling rates.

This technology can repair components which have been considered non-repairable by conventional methods.

It produces quality final products that not all the AM technologies can achieve. Only EBM, SLM and some MD processes look to be the most applicable technologies for high technical requirement parts.

LMD and WAAM are two of the different examples of MD Processes [25].

- Benefits
    - Quality final products that not all the AM technologies can achieve.
    - Material Efficiency that reduces waste.
    - As mentioned before, can repair components which have been considered non-repairable by conventional methods.
- Challenges
    - Process control is required to precise control of process parameters to achieve quality and consistency of the deposited material.

3.2. Materials used

A lot of research is going on for the use of different materials for AM. The different research goes for different types of metals (aluminum, steel, titanium), alloys, polymers, ceramic composites, that can be printed for the use in some fields including aerospace/aeronautical.

In the case of the aeronautical/aerospace industry, the most used metals for the production of components for aircrafts are based on alloys made of titanium, nickel, aluminum and some other metals.

Titanium

For titanium, the most used alloy for the aerospace industry is **Ti6Al4V** also known as TC4 or Ti64. It is an alloy composed of Titanium-Aluminum-Vanadium.

Originally, this alloy was created for the aerospace industry and now it is quite popular. Nowadays, this alloy is not only used for the aerospace industry, it is also used for the gas and petroleum market which is essential to have an alloy with a combination of high strength, corrosion resistance, and low weight.

- Applications in aerospace industry [28]
  - Turbine disks, rings and blades
  - Aircraft structural components
  - Rivets
  - Hand Tools
  - Valves and pumps

The chemical composition of **Ti6Al4V** (limits in %).

Titanium (Ti)	Rest of the alloy
Aluminum (Al)	5,50-6,75

Vanadium (V)	3,50-4,50
Iron (Fe)	max. 0,30
Oxygen (O)	max. 0,20
Hydrogen (H)	max. 0.125
Nitrogen (N)	max. 0.05
Carbon (C)	max. 0.08

Table 2. Chemical composition of Ti6Al4V alloy. Source: [28,29]

- Benefits
  - Excellent corrosion resistance
  - It has a good ductility and toughness
  - High temperature resistance
  - Non-magnetic properties
- Disadvantages
  - High cost
  - Welding difficulty
  - Notch Sensitivity (small imperfections on the surface)

Ti6Al4V offers several notable advantages and disadvantages. Among its benefits, the alloy exhibits excellent corrosion resistance, making it suitable for use in harsh environments such as marine and chemical industries. Additionally, Ti6Al4V possesses good ductility and toughness, allowing it to withstand significant deformation without fracturing, which is advantageous for dynamic applications. Its high temperature resistance enables it to maintain mechanical properties at elevated temperatures, critical for aerospace and automotive components exposed to high thermal stress. Moreover, its non-magnetic properties make it ideal for applications where magnetic interference must be minimized, such as in medical devices and sensitive electronic equipment.

However, Ti6Al4V also has its disadvantages. Welding Ti6Al4V can be difficult due to its tendency to absorb oxygen and nitrogen from the air, leading to brittle welds if not properly managed. Additionally, Ti6Al4V is prone to notch sensitivity, where small surface imperfections can significantly reduce its fatigue strength and overall durability, requiring careful handling and processing to avoid surface defects. Despite these challenges, the unique properties of Ti6Al4V make it a valuable material in various advanced engineering applications.

Inconel 718

Inconel 718 is a Nickel-Chromium-Molybdenum alloy which has some different applications in fields which require a combination of high strength, corrosion resistance, and low weight, as **Ti6Al4V**.

This alloy presents an excellent capacity to provide maximum strength and high resistance to deformation and tensile failure.

- Applications in aerospace industry [30]
  - Gas turbine engine parts
  - Liquid rocket engine components
  - Springs, rivets
  - Cryogenic vessels
  - Pumps and valves
  - Tools

The chemical composition of **Inconel 718** (limits in %).

Nickel + Cobalt (Ni+Co)	50-55
Chromium (Cr)	17-21
Iron (Fe)	Balance
Molybdenum (Mo)	2,8-3,3
Copper (Cu)	max. 0,3
Cobalt (Co)	max. 1

Carbon (C)	max 0,08
Manganese (Mn)	max. 0,35
Silicon (Si)	max. 0,35
Phosphorus (P)	max. 0,015
Sulfur (S)	max. 0,015
Titanium (Ti)	0,65-1,15
Aluminum (Al)	0,2-0,8
Niobium + Tantalum (Nb+Ta)	4,75-5,5

Table 3. Chemical composition of Inconel 718 alloy. Source: [30,31]

- Benefits
  - High strength
  - Excellent corrosion resistance
  - Superior weldability
  - Oxidation resistance
  - High temperature resistance
- Disadvantages
  - High cost
  - Relatively high density
  - Welding limitations
  - Susceptibility to stress-corrosion cracking

Inconel 718 offers several significant advantages. Inconel 718 is highly valued for its strength, essential for applications needing robust materials under mechanical stress. It boasts exceptional corrosion resistance, vital in demanding environments like aerospace and marine sectors. Its excellent weldability supports complex component fabrication and repair. The alloy's superior oxidation resistance and maintained mechanical properties at high temperatures make it ideal for extreme heat applications such as gas turbines and jet engines.

However, Inconel 718 also presents some disadvantages. Inconel 718's high production and processing costs restrict its application to cases where its advantages outweigh expenses. Its relatively dense nature can be a drawback in weight-sensitive applications. While it exhibits good weldability, specific techniques are necessary for welding integrity due to process limitations. Moreover, susceptibility to stress-corrosion cracking poses a risk in certain environments, potentially impacting long-term performance. Despite these challenges, Inconel 718 remains invaluable for high-engineering applications needing strength and durability in extreme conditions.

Both alloys are the most present in some research of AM in the aerospace/aeronautical field, because of their characteristics and the necessity of the industry of having resistant materials for the production of some components.

Metal Alloys	**Ti6Al4V**	**Inconel 718**
AM Process	EBM SLM WAAM	EBM SLM Other processes
Other Manufacturing Process	Typical Wrought Hot Worked and Annealed (Wrought) ISO 5832-3 (ISO Standard)	As-Cast Cast Inconel 718 Wrought Inconel 718 Injection Moulded Inconel 718 (as Sintered) Injection Moulded Inconel 718 (as aged) As Hot Isostatically Pressed AMS 5662G specification for Wrought material

Table 4. AM processes for Titanium and Nickel alloys. Source: Own work based on [24]

There are more of them mentioned in the following part, but it is important to make emphasis on these two alloys because of their recurrent appearance in some studies. But materials like polymers and other metals are also important.

Material	Material name and process	Characteristics
Polymers	Aluminum-filled polyamide 12 powder. (SLS)	• Excellent dimensional Accuracy • Good processing capabilities • High stiffness
	Carbon-fiber reinforced polyamide 12 (SLS)	• Metal replacement • Good strength-to-weight ratio • Lightweight
	PA 2210 FR (White polyamide 12 powder with a flame retardant additive) (SLS)	• Good mechanical properties • Flame retardant
	PA 3200 GF (Glass bead filled polyamide 12 powder) with SLS	• High stiffness • Wear resistance • Good thermal performance
	PPSF/PPSU (Polyphenyl sulfone) with FDM	• Good chemical and heat resistance • Good thermal performance
	Quantevo™-CF (PEAK-Polyarylether ketone)	• Carbon fiber reinforced • Non-corrosive • Excellent strength-to-weight ratio
	ULTEM™ 9085 with FDM	• Suitable for space applications • High strength-to-weight ratio • Suitable for space applications
	ABSi with FDM	• Translucent material • Durable
	Nylon 12 with FDM	• High fatigue endurance • Strong chemical

		resistance
Other metals	EOS Maraging Steel MS1 (Martensite hardenable steel) with DMLS	• Good strength • High toughness • Easy machinable • Good thermal conductivity
	Aluminium AlSi10Mg with DMLS	• Good dynamic properties • Good thermal properties • Low weight applications

Table 5. Different other AM Materials. From 3D Printing in aerospace and its long-term sustainability. Source: [24]

Limitations

AM materials face limitations such as dimensional stability, strength, viscosity, and resistance to heat and moisture. Weak bonding between layers can lead to delamination and breakage, especially in load-bearing parts. Defects like porosities and cavities can affect mechanical performance, which varies directionally (anisotropy). Incorporating fibers into the matrix powder improves mechanical properties, enhancing flexural strength and reducing porosity. [24].

Roughness and porosity are key factors influencing the fatigue behavior of printed parts. Studies have shown that higher surface roughness reduces fatigue life, while porosity is less impactful than the alloy's microstructure. Roughness depends on the printing technology and other process parameters [25].

To improve the mechanical properties, process parameters can be adjusted to achieve properties similar to those of conventional technologies. High cooling rates in AM produce small grain sizes, enhancing crack incubation periods and improving fatigue resistance at low temperatures. However, AM parts exhibit anisotropy, with the build direction being the weakest in terms of ultimate tensile stress.

It is necessary to make more studies and an expansion of powder-based alloys are needed for diverse applications. AM allows for the creation of "designed" materials with unique characteristics, and developing models that correlate final part characteristics with process variables is crucial for effective use in the aerospace industry.

3.3. Literature Review

AM is a technology that has gained significant traction over the past decade. It has shown promising development, extending beyond the printing of simple objects made from plastics to producing components for industries such as aerospace, automotive, and medical prosthetics, among others.

The readings on its multiple uses and implementation in the aerospace sector have provided us with some insight into how its utilization is being carried out. Currently, what has been read so far indicates that while AM is a technology that will see greater use in the future, it is not yet capable of replacing conventional production methods due to various factors, such as higher production costs and the scalability of AM. As a result, the production of components using this technology is temporarily limited to the production of discontinued maintenance parts, small-scale production of specific components, and prototype production, as has been done recently. The reason for this is the limited amount of dedicated studies and information on the subject.. Currently, research is ongoing into new metal alloys and AM processes to implement them in different sectors and to find ways to eliminate the current issues in order to increase its presence and make a more significant impact on companies' production and logistics processes.

Thanks to AM, components have been created that were never before possible, with more efficient designs and superior quality finishes that could not be achieved with conventional manufacturing. Additionally, it has been reported that with AM, recreated designs or products are easily recyclable, thus reducing the waste of raw materials or parts that cannot be recycled with conventional manufacturing. This offers the possibility of recovering up to 95% of the material used in the manufacturing process.

Various studies have been conducted on its productive, environmental, logistical, and economic impact. The estimated forecasts point to a positive direction if correctly implemented, as it is possible to optimize supply chain processes, save on the production of specific components, and reduce the environmental impact of both aircraft operations and companies due to the inherent characteristics of this technology.

There are various manufacturing processes depending on what needs to be printed, such as SLS, SLM, WAAM, or EBM [24,25,27] (among others), for printing with different metals or polymers. Companies like Stelia Aerospace, Safran Helicopter Engines, General Electric, and Airbus have already used AM for their products. General Electric created nozzles for a new engine to improve the injectors. Experimental nozzles were certified in 2016, and now the cost of orders is reported to have reached $22 billion. The manufacturer intends to produce 25,000 parts per year using three-dimensional printing technology. [35] Meanwhile, Airbus used AM components like a titanium 3D-printed bracket, which is part of the aircraft pylon, the junction section between wings and engines, on an in-series production A350 XWB and also for its A320 Neo aircraft [33]. AM is designed to facilitate aircraft construction by optimizing component geometry. In 2015, Stelia Aerospace used the WAAM AM process to produce an aircraft fuselage panel [34] .

It was also reported that companies like Safran Helicopters, presented a line of Aneto gas turbine engines presented by Safran Helicopter Engines in 2017. This compact power unit, with inlet guide vanes and a rotating combustion chamber made using the 3D printing method, is 30% more powerful than units of similar dimensions [35].

This confirms that, first, it is a technology with a bright future; second, it has different types of processes depending on the needs of the product to be produced; and third, companies are starting to use this technology and continue to research how to enhance its virtues seen to date.

4. Case Study: Implementation of new technologies in a Aeronautical Manufacturer

The purpose of this chapter is the development of a case study of implementing the new technologies from Industry 4.0 such as 3D Printing in an aeronautical manufacturer and see how this technology can benefit the company in terms of cost reduction, logistics, results and performance of the product or service provided by the manufacturer. The development of this case is based on some sources consulted before for making the project.

4.1. Description of the Aeronautical Producer or company

The company chosen for the case is the European manufacturer Airbus, the giant of European aviation that has been in the sector since 1970 as a European consortium with the mission of competing with its American counterparts Boeing and McDonnell Douglas. Airbus is a world leader in the aerospace industry, at the forefront of technological innovation, and actively participating in the Fourth Industrial Revolution. In recent years, it has begun integrating AM for the production of components for its aircraft.

The case study will be based on the bibliographic review used to carry out this final degree project, examining how AM and other technologies can help to improve the company's production processes and whether it can be a key element in the company's development in the sector and the development of its products.

4.2. Application of AM in the company

Airbus is already using 3D printing to manufacture components for its aircraft, such as the A320 Neo and the A350 XWB as mentioned before. Previously discussed functions of 3D printing at Airbus include part production, prototyping, customization, and maintenance and repair of aircraft.

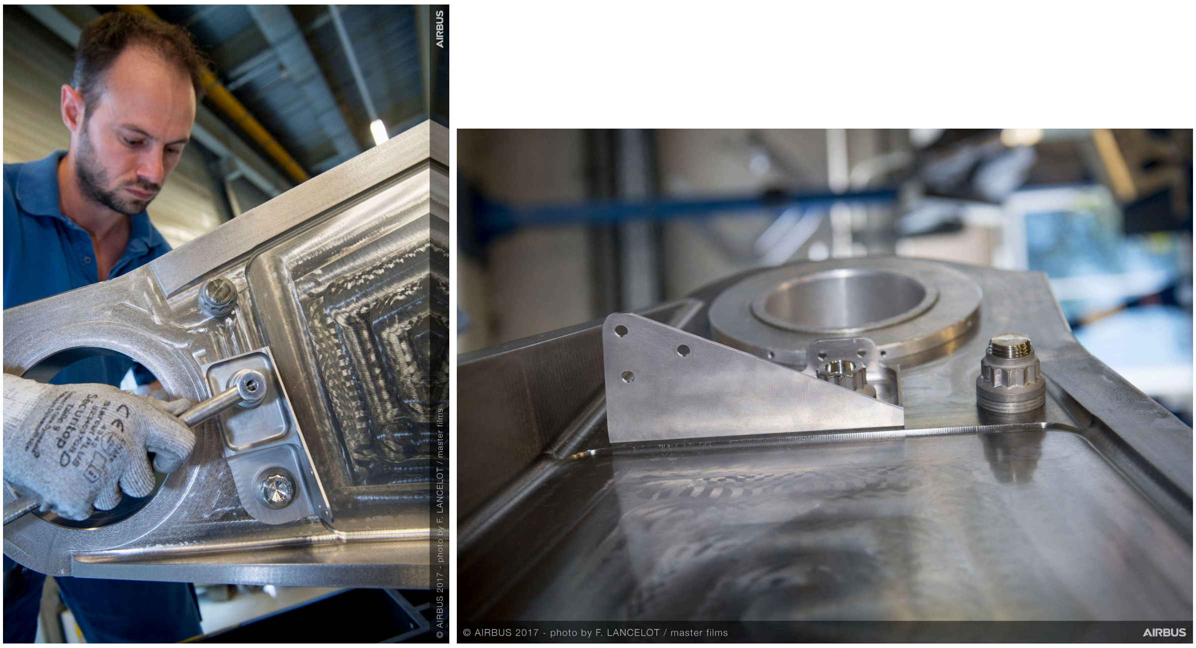

Image 1. 3D printed bracket installed on A350 XWB pylon. Source: [33]

In its Defense and Space division (Airbus Group's three divisions are Commercial Aircraft, Helicopters, and Defense and Space), Airbus has also created various AM parts for some of its military aircraft.

The material used for making these components is called **Scalmalloy**.

Scalmalloy is an aluminum-magnesium-scandium powder alloy designed for metal 3D printing, namely with **SLM** or **DMLS**. Its material properties combine the lightness of aluminum (**AlSi10Mg**) with almost the same specific strength and ductility of titanium (**Ti6Al4V**) [36].

MAW System Cover

The selected part is an external cover used in the MAW system installed in the C-295 (a light and medium aircraft).

[38].

Image 2. An Airbus C295 from the Spanish Army. Source: [37]

The decision to use this application for an AM prototype is due to the current high lead time for this spare part.

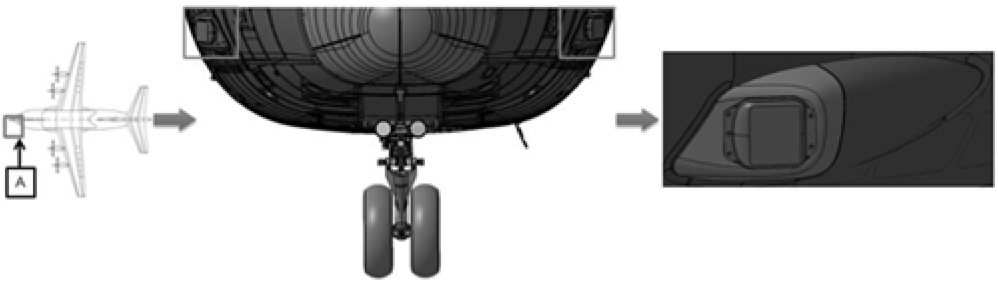

Figure 17. Location of the external cover of the MAW System. Source: [38]

Small changes were implemented to adapt the current design to one more suitable for AM technology. Using available software, minor adjustments were made to avoid surfaces below 45º relative to the printing direction, while the external surface had to maintain its original geometry due to aerodynamic requirements. Simulating a real qualification process, inspections were conducted, and witness samples were printed in the same batch as the parts [38].

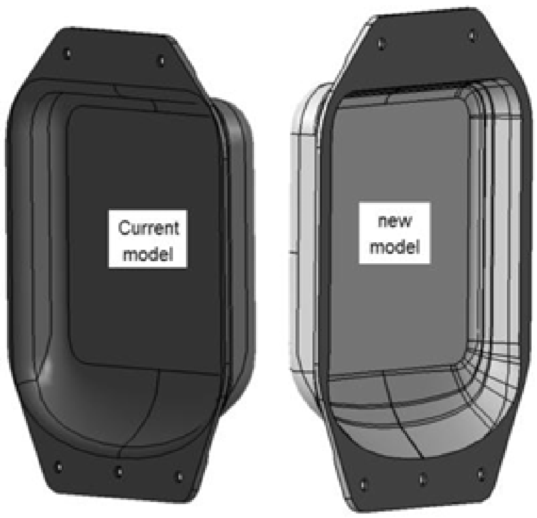

Figure 18. Design of the current cover vs the AM cover design. Source: [38]

Drain Mast

This focuses on the redesign of the A400M Fuel Drain Mast Assembly to leverage the benefits of AM.

Image 3. An Airbus A400M Atlas from the Spanish Army. Source: [39]

The assembly, with dimensions of 338.4 x 166.7 x 50 mm, is currently manufactured by welding parts made of aluminum 3.3214 [38].

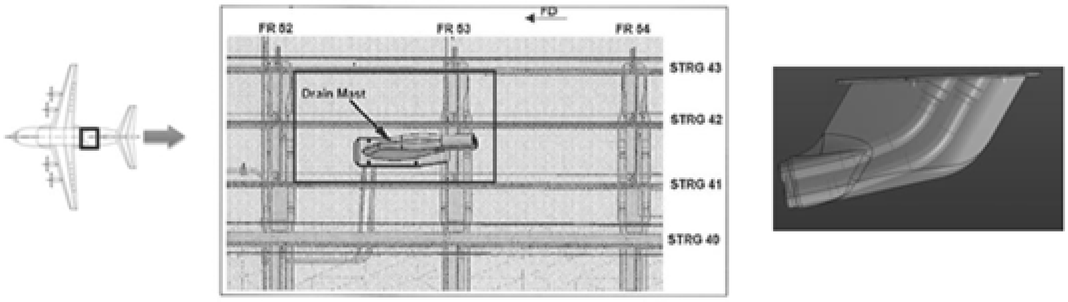

Figure 19. Location of the Drain Mast of the Airbus A400M. Source: [38]

To make a prototype for this design, Airbus made several steps to achieve it. An analysis of the requirements (Ex. Aerodynamic considerations, inspections, structural requirements, reparability, ...) was carried out including an analysis in the features for the redesign in AM which focuses on maintaining essential aspects for compatibility and performance. Key features include preserving attachment points and the overall footprint, ensuring existing hole locations are kept for proper installation, and adding 2mm material allowance to the flange for a proper seal. Pads are added to interfaces for milling bearing areas, ensuring screws fit correctly. Consistent angles for drainage pipes are maintained for proper fit, and the aerodynamic surface is designed to match or exceed the original part's performance [38].

A 3D model is done with the information mentioned above, ensuring that the printing machine has the capabilities to produce the component, accounting for surrounding structures for the component that may limit the part’s volume [38]. Airbus commented that the goal of the design was to maintain the original outer shape for flight physics requirements, but this was abandoned due to inspection limitations. An optimized design was then developed, resolving inspection issues but facing manufacturing constraints at the exhaust area. Final iterations focused on retaining the optimized aerodynamic shape while ensuring manufacturability.

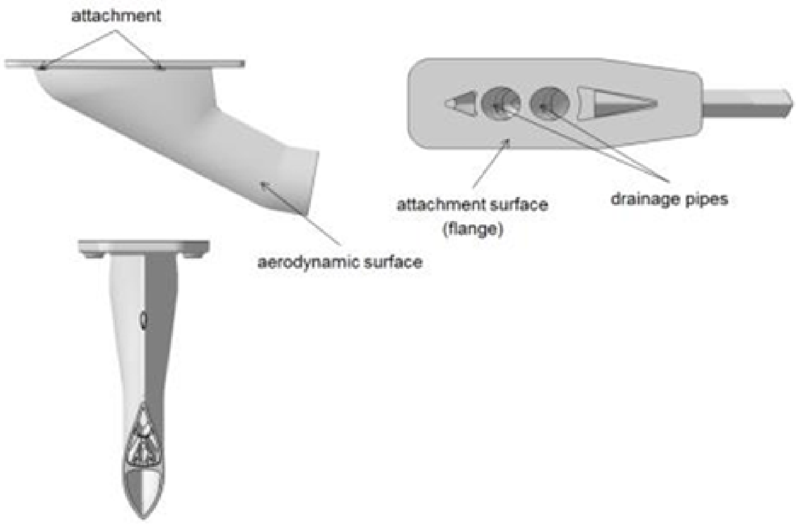

Figure 20. Final design of the Drain Mast in AM. Source: [38]

Fuel Pipe Bracket

This component was selected due to the identified potential for weight reduction and a positive business case, given the high buy-to-fly ratio, which is the volume ratio between the raw material needed for manufacturing and the final part.

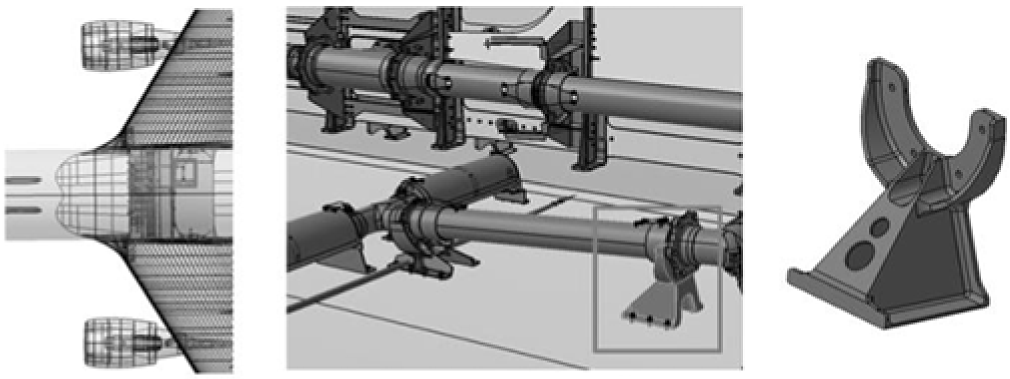

Figure 21. Location of the Fuel Pipe Bracket. Source: [38]

Based on the latest topology optimization results, a new design was proposed and subsequently printed. Reconstructing the geometries from topology optimization can be challenging using traditional design tools. Therefore, in recent years, design software companies have developed specific tools for this type of AM design. The final design achieved a 31% mass reduction while meeting the same structural requirements for strength and stiffness as the original design [38].

Image 4. Fuel Pipe Bracket created by AM. Source: [38]

This is a documented example of how Airbus is using the AM for the production of prototypes of some different components for the military aircrafts like the A400M or C295. It is also implemented in commercial aircrafts like the A350 XWB where the fuselage and wing designs are made of a carbon fiber reinforced polymer, as mentioned in the Literature Review.

4.3. New specific component printed

Given the applications that the European company has given to AM in its defense and space division, the virtues of this technology can be seen, for example, for the production of prototypes or spare parts that may take too long to arrive. It is important to know that AM within the aeronautical sector can be divided into three types:

- Complex engine parts
- Structural components
- Replacement parts

To carry out this case, a safety component has been chosen that we always see when we fly on a commercial airplane but that not everyone thinks about when they get on a plane, which is the seat belt.

Image 5. Typical Seat Belt from a commercial flight. Source: [40]

Seat belts are basic yet crucial components to ensure passenger safety during the most critical moments of flights, which are takeoffs and landings, as well as during any turbulence that may occur during the flight [41].

They are composed of two key parts, the belt strap and the buckle.

- The strap is made of high-strength nylon or polyester and has a length of 78 to 125 centimeters [41].
- Meanwhile, the buckle is usually made of high-strength steel or aerospace-grade aluminum.

A new version of the buckle created by AM is proposed and compared with one created by conventional methods.

	Conventional Seat Belt Buckle	AM Seat Belt Buckle
Material	Steel or Aluminium	Titanium [42] or Scalmalloy
Process	Injection molding and Forging	SLM or SLS
Advantages	• Buckles made with conventional methods, such as molding and machining, have been tested and used for decades, proving their reliability, durability and quality in real-world conditions. • The materials and traditional manufacturing processes ensure high mechanical strength, capable of withstanding significant forces and stresses without deforming. • Traditional methods provide the required reliability and quality control procedures for the buckles.	• Component is lighter than the traditional component. • To lower the cost of ownership, cut labor costs, and boost operational availability for airplanes. • Design optimization • Fly-buy-ratio: Given that the buy-to-fly ratio of an AM part can be as low as 1:1, AM looks to be the best option. [52]
Disadvantages	• Slower production processes. • Components are heavier than those produced by AM. • Higher buy-to-fly ratio. Buy-to-fly ratios for items produced using conventional techniques are typically about 15-20. [52] • Conventional manufacturing methods are often limited in terms of design flexibility and complexity. • Traditional manufacturing processes tend to	• Further research and development are necessary to ensure its viability in safety-critical applications. • Although AM technologies have advanced significantly, parts can exhibit inconsistencies in their structure due to the layered material, which could affect their long-term durability. • Parts produced by AM can have internal micro-defects or variations in material density that may compromise their

	produce more material waste compared to AM.	mechanical strength. ● Considering the stringent certification requirements and performance expectations that AM could not have. ● So expensive right now, in terms of energy consumption, to make a massive production.

Table 6. Comparison of the Conventional Seat Belt buckle vs AM Seat Belt buckle. Source: Own Work.

The weight difference it's vital in the aerospace sector for topics related to aircraft efficiency, reducing the weight of components that may not seem relevant at first glance can have a significant impact on the efficiency of the aircraft. That's why something like a seatbelt is an interesting choice to make a weight reduction.

A commercial seat belt buckle has a weight of 155 grams made of steel while an AM seat belt buckle made of a titanium alloy has a weight of 68 grams [42].

Conventional Seat Belt Buckle	**AM Seat Belt Buckle**
155 grams	68 grams
Reduction of 87 grams/buckle (Weight reduced in 55%)	

Table 7. Weight comparison between conventional and AM Seat Belt Buckle. Source: Own work based on [42]

Image 7. A comparative image of conventional seat belt buckles vs an AM prototype version of a Seat Belt Buckle. Source: [42]

4.4. Results

4.4.1. Benefits and challenges

Figure 22 shows the different operational costs incurred by an airline when having an aircraft in operation. As can be seen, the highest cost per aircraft is fuel consumption, with a difference of 22.8% compared to owning an aircraft. It is the highest cost and the one that has a significant impact on ticket prices.

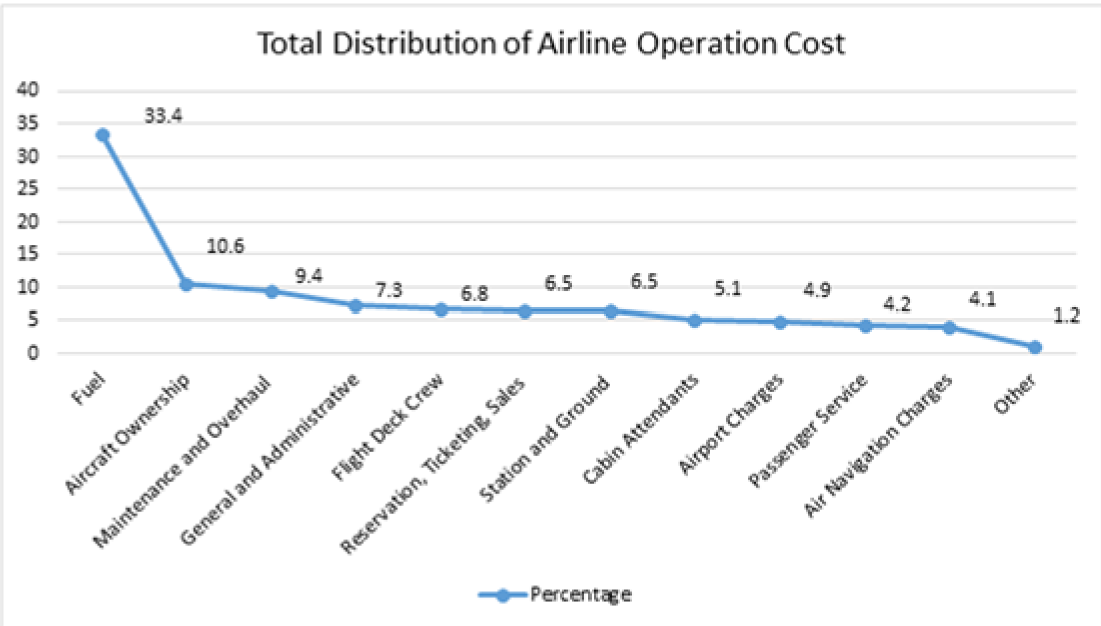

Figure 22. Total distribution of Airline Operation Cost. Source: [43]

There are various ways to achieve a reduction in operational costs, with special emphasis on fuel expenses. One way to reduce this cost is by optimizing flight route planning, analyzing current traffic and the aircraft's speed. Another way is through proper maintenance, where engines and the aircraft's infrastructure are checked. Another method is by reducing the aircraft's weight, where the weight of non-essential cargo and unnecessary luggage can be reduced, or through the implementation of lighter materials and components in the construction of the aircraft, this is where AM comes into play.

According to different sources, the use of AM for the production of aircraft components has a positive impact on reducing fuel costs due to the weight reduction of the aircraft. According to T. Saracyakupoglu, "Reducing the weight of each aircraft in a fleet of 600 commercial airplanes by 1 kg could help save 11,000 barrels of fuel annually." Additionally, he mentions that reducing the weight of an aircraft by 1 kg reduces the carbon emissions of an Airbus A330 by 0.475 kg [43,44].

Reducing carbon emissions by 1 kilogram reduces fuel consumption by 0.3 kilograms [44]. There is a study on what would happen if conventional seat belts on an Airbus A380 were replaced with others produced using AM. The results of this study conducted by Airbus, called the SAVING Project, showed that if the weight of the seat belt buckles were effectively reduced by 55%, the total weight of the aircraft would decrease by 72.5 kg [43,44,45]. This would result in a total fuel savings of 3.3 million liters over the aircraft's lifetime, whether it is the A380 or another model [42,43,44,45].

The advantages that AM can bring to the production of seat belt buckles include:

- Revolutionizing design by eliminating traditional assembly and manufacturing limitations, as AM does not require molds or forging to produce the part.
- Providing more innovative and efficient seat belt buckle designs while reducing inventory and maintenance costs.
- Enabling rapid production of spare parts, which streamlines airline operations and reduces supply chain complexity by bringing manufacturing closer to points of assembly, use, and maintenance.
- Reducing logistical costs and environmental impact by allowing local production, eliminating the need to transport parts from different countries.
- Making the supply chain more efficient and less risky, as seat buckles can be manufactured on demand, reducing the need for safety inventories.

The challenges that could arise if AM were implemented in this case could be several. As previously mentioned, strict safety protocols must be met, where the seat belts must undergo optimal quality control to ensure they provide the same safety as traditional ones in the event of an accident. They must also be certified by competent authorities such as EASA or the FAA, which, despite having guidelines on AM, may or may not accept the parts if they do not meet the required technical standards.

Another challenge, if the project to use AM for the production of seat belt buckles moves forward, is scalability. Currently, AM is perfect for small-scale production of individual parts, rapid prototyping, and replacements that are slow to arrive or no longer exist, but it is not suitable for large-scale production due to its high energy costs, production speed, and other factors.

4.4.2. Impacts in the Supply Chain

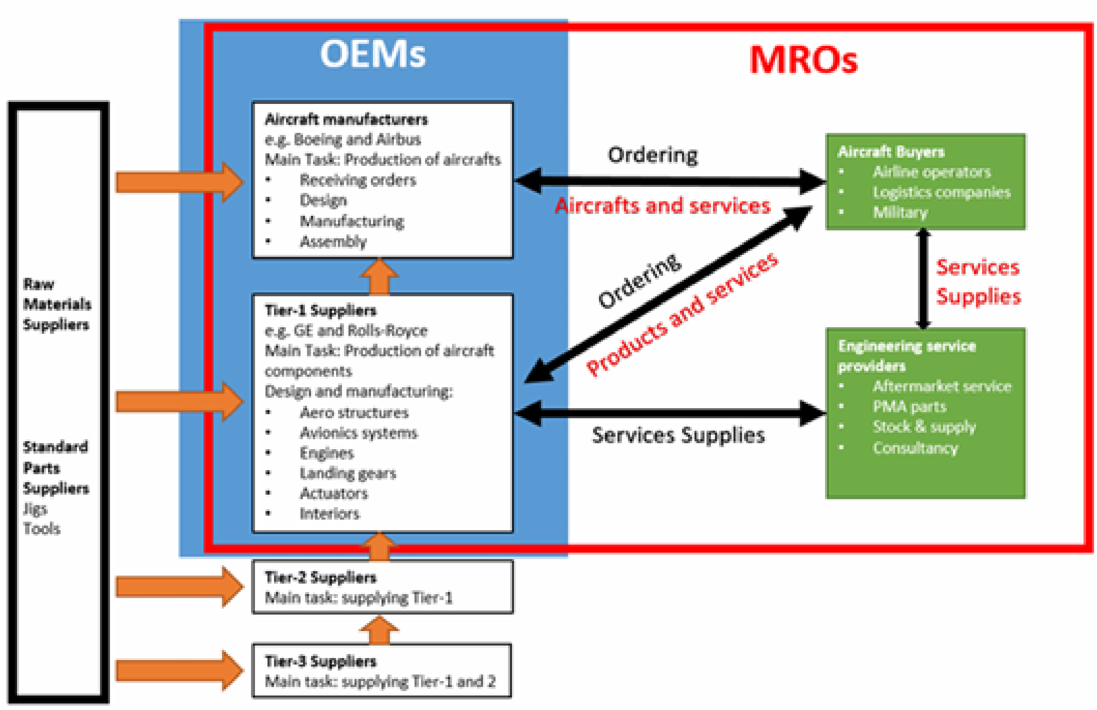

Figure 23. The aircraft industry production and maintenance models. Source: [46]

Maintenance, Repair, Operations (MRO) activities account for 40-50% of the aerospace industry's revenue, and selling spare parts is more profitable than selling the original equipment. Aircraft components, which require rigorous inspections and have unpredictable demand, stretch inventory levels to the limit, even though only 10% require regular replacement [46].

The supply chain faces complications that result in delays and higher costs. Customization of components and late design decisions increase complexity and production costs. Long procurement times force the maintenance of high levels of safety inventory, tying up capital.

AM can have various impacts within the supply chain. It can directly strengthen the Product Lifecycle Management (PLM) of seat belts, facilitating the management of product lifecycle in aviation, improving innovation, traceability, and communication among stakeholders.

AM can strengthen PLM by:

- **Rapid prototyping:** Accelerates product development and launch, allowing for the evaluation of performance and customer satisfaction [46].
- **Rapid manufacturing:** Can be applied in the production of parts and packaging systems, reducing production and MRO costs and times. AM can lower storage and distribution costs and enables on-demand production of parts, decreasing production and MRO times and costs [46].
- **Rapid tooling:** Facilitates the on-demand manufacturing of specific tools, especially benefiting MRO and final disposition, where service providers manage various types of aircraft requiring different tools for disassembly, repair, and assembly of systems and parts [46].

The implementation of Industry 4.0 technologies, in addition to AM, also influences the supply chain and SCM. Using technologies such as IIoT, Big Data, Blockchain, or AI for inventory optimization allows real-time monitoring of inventory levels and demand, improving management and reducing the risk of shortages. For example, traceability and transparency of the chain can be improved through Blockchain and IIoT, where Blockchain creates records of every transaction in the supply chain and IIoT monitors the status of components in real-time, ensuring that they meet safety standards. Robotics and automation increase operational efficiency, reducing errors and improving product quality. Additionally, with Industry 4.0 technologies, predictive maintenance based on sensors and data analysis can reduce downtime and extend the lifespan of equipment.

4.4.3. Lessons learned and future perspective

- It is a technology that can bring benefits to Airbus beyond just prototype production.
- It can help reduce the number of intermediaries in the supply chain by promoting the local production of spare parts or components without needing to order from an external intermediary, possibly from another country.
- The direct manufacturing of components without using molds or forging reduces operational costs and benefits small-scale production.
- Buckles made by AM need to undergo a series of quality checks to ensure that there are no defects in the final product.
- These components must be certified by competent authorities (EASA, FAA, ...) to ensure their use in aircraft.
- It is a sustainable technology. One of Airbus's goals for 2035 is to use sustainable aircraft, making them zero-emission or low-emission. This is why various technologies, such as AM, come into play.

Airbus's future prospects are favorable, with the belief that this technology will revolutionize the industry due to its multiple benefits, such as weight reduction, reduced aircraft emissions, and shorter delivery times. Airbus will invest in Industry 4.0 technologies to achieve its goals of optimizing aircraft operations and reducing environmental impact.

It is an innovative technology, and as it matures, it will be used more widely, with standardized and regulated use in terms of materials, processes, and the quality of manufactured products. If AM reaches a good level of maturity and popularity among the majority of producers, it would not be unreasonable to think that seatbelt buckles could be manufactured using AM instead of conventional production processes.

5. Discussion

In this study, the impact of AM within the aeronautical sector, specifically for an aircraft manufacturer, was investigated. The results indicated that the implementation of this technology brings benefits to conventional production processes and produced products, as well as some disadvantages.

Various previously consulted studies mention that AM produces better material utilization, customization, shorter lead times for small batch production, and, most importantly, improved supply chain structures, addressing the fundamental issues and concerns of the aircraft industry. By incorporating AM techniques, the aviation industry can benefit from reduced aircraft weight, which lowers fuel consumption and, in turn, reduces carbon emissions. AM processes appear almost perfectly suited to the aviation industry, allowing lighter parts to be produced at a lower cost but with mechanical features equal to conventional machining techniques.

The aircraft sector seems to be a near-perfect fit for AM procedures since they enable the production of lighter parts with comparable mechanical properties at lower costs than traditional machining methods. One of the main barriers that will negatively impact fatigue life is surface finish. Limitations on build size also hinder the spread of the technology. These and other reasons make it more difficult for aviation authorities to certify parts made using AM.

There are also other challenges, such as the high cost and the scalability of production due to the speed of AM in manufacturing, which are present when trying to implement this technology on a large scale. It is important to consider the limitations of this study, as it is based on hypothetical scenarios of what would happen if AM were implemented. To confirm this, future research and increased real-life applications are needed to corroborate the findings.

This study aims to contribute a small part to the implementation of AM in the sector to improve not only production processes but also the aircraft produced with this technology. The goal is to achieve a more efficient future, both environmentally and in optimizing airline operations concerning fuel consumption, which has been shown to be their most significant expense.

6. Conclusions

During this thesis, the impact of AM within the aerospace industry has been examined, specifically in the production of components and its impact on various fields such as aircraft performance and logistics.

To address these topics, a comprehensive literature review was conducted to broadly explain the multiple virtues and defects that this technology brings to the products or services that use it, as well as the impacts it generates in other related areas.

The results revealed that it is a technology that offers various benefits to companies if actively implemented in aspects such as optimized design for weight reduction, reduced fuel consumption, and reduction in supply chain intermediaries among different actors within the component production field.

It was also observed that there are already several producing companies in the sector, such as Airbus, studied in this work, that are implementing it in various aircraft as replacement parts and prototypes, also for parts of their aircraft infrastructure or in future projects where the use of AM will have a much greater role.

The findings of this research have important theoretical and practical implications. From a theoretical perspective, it highlights the pros and cons of AM, as well as its various technologies applied to the sector and some of the materials (alloys) used for the production of components suitable for the aerospace sector. On the practical side, the case study on the implementation of seat belt buckles made by AM has shown that if the weight of the buckles were reduced by 55%, a total of 72.5 kg could be saved from the weight of an aircraft such as an Airbus A380, which would mean, according to various sources consulted, a reduction of 3.3 million liters of fuel consumption over the aircraft's entire lifespan. Another study mentions that by reducing just 1 kg of weight from each aircraft in a fleet of 600 commercial airplanes, 11,000 barrels of fuel could be saved annually.

6.1. Summary of the benefits and challenges of AM

During the work, a series of benefits and drawbacks have been identified, which are worth considering to determine whether it is worthwhile to implement AM within the aerospace sector or not.

Benefits

- **Reduction in fuel consumption**: Lighter aircraft due to the virtues of AM.
- **Supply chain changes**: Fewer intermediaries may be needed.
- **Reduction in pollution**: Both in aircraft emissions and in production processes.
- MRO facilities are seeing the advantages of AM for component production.
- **Reproduction of discontinued parts**: A good option for manufacturing discontinued or slow-to-arrive parts.
- **Adoption by major producers**: Large manufacturers like Airbus see it as a good opportunity and are applying it.
- **Rapid prototyping**: AM enables quick prototyping of components.
- **No need for molds or forging**: Unlike conventional manufacturing, AM does not require molds or forging to produce components.

Drawbacks

- **Limited to small-scale production**: Currently only useful for small-scale production.
- **Slow production speed**: AM is slower compared to traditional manufacturing methods.
- **High machinery costs**: The equipment used for AM can be extremely expensive.
- **Quality issues**: AM components can have quality problems such as cracks, pores, or microfractures.
- **Lack of standardization**: Absence of regulations to standardize AM processes.
- **Size limitations**: Production is limited by the size of 3D printers, requiring the production of smaller components that must then be assembled.
- **Cost of alloys**: Depending on the alloys used, materials can be more expensive than those used in conventional manufacturing.

6.2. Projection of the future of AM in the Aeronautical Industry

As seen in various sources consulted, more and more Original Equipment Manufacturer (OEM) and MRO manufacturers are showing increased interest in AM for the production of individual parts or replacements.

The overall outlook is positive, with producers beyond Airbus implementing AM in their production processes. For example, General Electric is producing 3D-printed nozzles for a new engine to improve the injectors and aims to produce 25,000 parts annually. Similarly, in 2017, Safran Helicopter Engines developed a compact power unit with inlet guide vanes and a rotating combustion chamber made by the 3D printing method, which is 30% more powerful than units of similar dimensions.

As AM technologies become more cost-effective and standardized, it is expected that more companies within the sector will follow suit. Airbus, for example, plans to transition to AM for at least half of its future aircraft components. This shift not only highlights the growing acceptance of AM in aerospace but also underscores its potential to revolutionize manufacturing processes, enhance component performance, and contribute to overall industry efficiency and sustainability.

Looking ahead, continued advancements in AM technologies, coupled with broader industry adoption, are poised to drive significant innovation and transformation within the aeronautical sector, paving the way for more efficient, reliable, and environmentally sustainable aircraft production.

6.3. Limitations and Suggestions for Future Research

Despite the significant findings, this study presents some limitations. It has relied on literature review, and the identified case studies may not necessarily reflect absolute truths about whether the implementation of AM in the sector can be as beneficial as claimed, but rather provide information based on hypothetical assumptions from various studies on what would happen if implemented. It is undeniable that AM will bring multiple benefits (as mentioned throughout this study), but its real impacts cannot be openly assessed until it is actually applied in real-world scenarios.

For future research, it could be beneficial to implement components produced by conventional methods such as welding and forging, such as seat belt buckles, and assess whether the weight reduction provided by AM technology would effectively reduce carbon footprint and fuel consumption. It is recommended to conduct comparative studies between an aircraft with AM-produced parts and an identical one with conventionally produced parts to identify their most significant differences.

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Annexes

World Information and Communications Technologies (ICT) Development Index is a tool used for measuring the level of development of a country's information and communication technology (ICT).

Galvanometers: Galvanometers are electromechanical devices that convert an electrical signal into angular motion. Essentially, they consist of a mirror mounted on an axis that can rotate in response to an electric current, allowing the laser beam to be directed with high precision and speed.

Buy to fly ratio: Refers to the weight difference between a component's end product and its original raw material. [44]