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A Sustainable Business Model for Aircraft Logistic Support Powered by Additive Manufacturing

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SUMMARY

This thesis explores the integration of Additive Manufacturing (AM) in the logistics and supply chain of Leonardo S.p.A.'s Aircraft Division, with a particular focus on developing a business model for the production of polymer parts. Leonardo S.p.A. is a global leader in Aerospace, Defense, and Security, renowned for its advanced technological solutions and commitment to quality and sustainability. The company offers a diverse range of products, including helicopters, aircraft, unmanned aerial vehicles, and electronic systems, serving both military and civil markets worldwide. Notably, Leonardo already employs AM-produced parts in its operational vehicles, underscoring the company's commitment to innovative manufacturing methods.

Aimed at enhancing efficiency in the provision of spare parts and Ground Support Equipment (GSE), this study highlights AM's potential to reduce lead times, enable on-demand production, and improve flexibility within manufacturing processes. Emphasis is placed on Fused Filament Fabrication (FFF) and Powder Bed Fusion (PBF) technologies as primary methods for polymer and metal parts production, respectively.

Prior to proposing AM as a transformative solution, an in-depth analysis of the company's existing operational framework was conducted to ensure alignment with Leonardo's strategic and logistical practices. This preparatory study provided essential insights into how such a disruptive innovation could be integrated effectively within current systems. The proposed business model leverages a performance-based approach, aligning production capabilities with client demand while ensuring cost predictability. An economic analysis demonstrates that, under specific assumptions regarding demand levels, operational scale, and resource allocation, the model is profitable. The study finds that the AM-based model offers competitive advantages over traditional manufacturing by reducing the need for extensive inventories and capital investment in tooling, particularly in low-to-moderate demand scenarios. Additionally, the model's flexibility and adaptability present long-term cost savings by mitigating risks associated with obsolescence and storage, thereby supporting a scalable, financially sustainable solution.

These findings underscore AM's strategic role in reducing obsolescence risks, supporting sustainability goals in line with the European Green Deal, and enhancing supply chain resilience in the Aerospace and Defense sectors. Ultimately, this thesis provides insights into the economic, operational, and environmental advantages of AM for polymer and metal parts production.

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CHAPTER 1: THE PROJECT “AM4LOGISTICS”

1.1 Project introduction: AM4Logistics

The project AM4Logistics, promoted by the Customer Support and Services of Leonardo Aircraft Division (LAD), aims to structure the integration of Additive Manufacturing (AM), also known as 3D Printing, within the supply chain of spare parts as well as Ground Support Equipment (GSE) to valorize the Logistic Support towards its clients. LAD offers integrated logistics services designed to best support fleets, maximizing availability and competitiveness in terms of time, quality and cost for the whole life cycle of the product.

The aim of this thesis is to develop a sustainable business model that harnesses the unique features and capabilities of Additive Manufacturing to enhance the logistics support services within the Aircraft Division, specifically in the provision of spare parts and GSE. By integrating AM into the supply chain, this work seeks to explore innovative ways to optimize efficiency, reduce lead times, and improve overall service quality of the Logistic Support.

Logistic support plays a pivotal role throughout the entire product life cycle, serving as a fundamental component in ensuring both aircraft availability and maintaining the airworthiness and safety standards. Two critical factors in this context are the availability of parts and their readiness, particularly when dealing with Aircraft Out of Commission for Parts (AOCP) events. Minimizing downtime is crucial for guaranteeing that aircraft remain operational and for reducing associated costs. Provisioning to clients is organized around a series of dedicated warehouses that serve as a pool of available spare parts, where components are ready for delivery upon customer request. This approach requires managing the pool through strategies and algorithms that allow for the analysis of the Risk of Shortage and the consequent timely replenishment to ensure availability. The complexity of planning activities, combined with production and logistic considerations, can sometimes lead to unacceptable delivery times and costs for spare parts. The integration of Additive Manufacturing technologies enables the optimization of a logistical plan by leveraging the benefits of agile production.

Additive manufacturing allows for on-demand production, reducing the need for large inventories and enabling faster response times to replace critical components. By minimizing lead times and material waste, additive manufacturing not only enhances the efficiency and flexibility of production processes but also contributes to cost savings and sustainability. As the aerospace industry continues to evolve, the adoption of additive manufacturing for parts production, spare parts in particular, represents a strategic innovation that can significantly enhance the supply chain in several ways that are summarized below.

Reduced Lead Times: AM allows for the on-demand production of spare parts, which can significantly reduce lead times. Traditional manufacturing methods often require long production runs and rely on complex supply chains that involve multiple suppliers and logistics. In contrast, AM enables manufacturers to produce parts quickly and locally, eliminating the need for long wait times associated with shipping and reducing inventory requirements. This is especially beneficial for critical industries like aerospace and defense, where downtime due to part shortages can be very costly.

Lower Inventory Costs: With the ability to produce parts as needed, companies can adopt a "just-in-time" inventory strategy, minimizing the need to stockpile large quantities of spare parts. This reduces the costs associated with storing, managing, and maintaining inventory, and decreases the risk of obsolescence, especially for parts that may become outdated or are only needed infrequently. By reducing inventory levels, companies can free up capital and reduce storage costs.

Customization and Flexibility: Additive manufacturing allows for greater customization of parts, which can be tailored to specific requirements without the need for retooling or additional setup costs that are typical in conventional manufacturing. This flexibility is particularly useful for producing obsolete or low-demand parts, as it removes the need for manufacturers to maintain a large inventory of every possible part variation. AM can produce complex geometries and integrated components that would be difficult or impossible to achieve with traditional methods, enhancing the performance and longevity of the parts.

Reduced Waste and Environmental Impact: AM processes typically use only the material necessary to create the part, significantly reducing waste compared to traditional subtractive manufacturing methods, which often involve cutting away excess material. This not only lowers material costs but also reduces the environmental impact associated with the production of spare parts. Furthermore, the ability to produce parts locally reduces the carbon footprint associated with shipping and logistics.

Enhanced Supply Chain Resilience: Additive manufacturing can increase the resilience of supply chains by reducing dependency on single suppliers and decreasing the risks associated with global supply chain disruptions, such as geopolitical tensions, natural disasters, or pandemics. By decentralizing production, companies can manufacture spare parts closer to the point of need, thereby mitigating risks associated with long supply chains and reducing the likelihood of production delays.

Improved Part Performance: AM allows for the creation of parts with improved performance characteristics, such as lightweight structures or optimized strength-to-weight ratios, which can be particularly advantageous in industries like aerospace and automotive. These parts can be designed with complex internal geometries that are not possible with traditional manufacturing, enhancing their functionality and durability.

Obscolescence Management: Obsolescence is defined as the condition affecting supply items essential during the product's operational lifecycle that are no longer available, supportable, or repairable by the company or its suppliers. The issue of technological obsolescence and the reliability of supply, maintenance, and support sources is particularly significant in the Aerospace and Defense sector. This challenge arises when the primary system's lifecycle far exceeds that of its components, with product lifecycles in this sector sometimes extending beyond 30 years. Additive Manufacturing emerges as a technology with the potential to mitigate supply issues related to obsolescence, either as a definitive solution or as a temporary buffer while an optimal solution is structured. The issue of obsolescence and how AM can provide support will be discussed in Section 3.5.5.

By enabling on-demand production, reducing waste, and enhancing supply chain resilience, AM can significantly streamline the spare parts supply chain, resulting in cost savings and improved service levels for companies.

The project largely meets the new sustainability directives, for instance through the reduction of emissions in both the manufacturing and delivery phases. Among other peculiarities, the additive technologies allow a significant reduction of the so-called buy-to-fly ratio, which goes from values of 12:1 for machining by material removal to about 1:1, with a considerable reduction of waste. The activity is also part of the European Green Deal plan, remaining in line with the planned reduction of greenhouse gas emissions by 55% by 2030 compared to 1990 levels.

1.2 Company Overview

Leonardo S.p.A. is a global leader in aerospace, defense, and security, renowned for its innovative technological solutions and comprehensive service offerings. Headquartered in Rome, Italy, Leonardo operates in over 150 countries with a workforce of approximately 50,000 employees. The company's core business segments encompass Helicopters, Aircraft, Aerostructures, Electronics, Cybersecurity, and Space, making it one of the world's most diversified industrial groups in these sectors.

Founded in 1948 as Finmeccanica, the company underwent a significant transformation in 2016, rebranding as Leonardo in honor of the Italian polymath Leonardo da Vinci, symbolizing the company's commitment to innovation, creativity, and excellence. This transformation marked a strategic shift towards focusing on high-technology and innovation-driven solutions across its various business sectors. Today, Leonardo is recognized for its commitment to safety, performance, and sustainability, underpinned by a robust portfolio of products and services designed to meet the evolving needs of its global customer base, which includes governments, institutions, and private organizations.

Leonardo's Helicopters division is a major contributor to the company's overall revenue, generating approximately 35% of total sales. The division produces a broad range of civil and military helicopters known for their versatility, reliability, and advanced technology. Leonardo's helicopters are used in various applications, from search and rescue and law enforcement to corporate transport and offshore operations. The Aircraft division, responsible for about 30% of the company's revenue, designs and manufactures fighter aircraft, unmanned aerial systems (UAS), trainer aircraft, and specialized mission aircraft. This division serves both military and civilian markets worldwide, with key programs including the Eurofighter Typhoon, M-346 advanced trainer, and C-27J Spartan tactical transport aircraft. Leonardo's Aircraft division is also heavily involved in next-generation fighter development through its participation in the Future Combat Air System (FCAS) and Tempest programs, aimed at bolstering Europe's air combat capabilities.

The Aerostructures segment, contributing around 10% of total revenue, focuses on the development and production of major structural components for commercial and military aircraft, such as fuselages and wings, demonstrating Leonardo's integrated approach to aerospace manufacturing. This division supports major programs for both civil and military customers, including components for the Boeing 787 Dreamliner and Airbus A321.

Leonardo's Electronics division, which accounts for about 20% of total revenue, provides cutting-edge solutions in avionics, communications, radar, and electronic warfare systems. These solutions cater to the defense, aerospace, and security sectors, offering critical technologies that enhance situational awareness and operational effectiveness. The Cybersecurity division, representing roughly 5% of revenues, delivers advanced solutions to protect critical infrastructure and secure communications networks, reflecting Leonardo's commitment to addressing growing cyber threats globally.

The Space segment, though smaller in revenue contribution, plays a significant role in Leonardo's portfolio through joint ventures such as Thales Alenia Space and Telespazio. This segment is involved in satellite manufacturing, space exploration, and ground systems, contributing to the global space industry and supporting scientific missions, Earth observation, and telecommunications.

Committed to sustainability and responsible innovation, Leonardo integrates environmental, social, and governance (ESG) considerations into its business strategy. The company is dedicated to reducing its environmental footprint and enhancing its societal impact through initiatives that promote diversity, inclusion, and ethical conduct. Furthermore, Leonardo invests significantly in research and development (R&D), collaborating with academic institutions, research centers, and industry partners to advance technological capabilities and drive future growth.

With a strong financial position and a well-diversified product portfolio, Leonardo S.p.A. continues to be a pivotal player in the global aerospace, defense, and security landscape, leveraging its heritage, expertise, and innovative spirit to shape the future of these industries.

https://www.leonardo.com/en/press-release-detail/-/detail/07-05-2024-leonardo-1q-2024-financial-results

CHAPTER 2: SPARE PARTS LOGISTIC MANAGEMENT

2.1 Introduction

The Aerospace and Defense (A&D) industry is characterized by the high complexity, criticality, and stringent operational requirements of its systems. Maintaining the operational readiness of aircraft and defense equipment is crucial, as downtime can have significant financial, operational, and even national security consequences. This involves a comprehensive approach to inventory management, supplier coordination, logistics planning, and demand forecasting. The optimization of these processes ensures that the right parts are available when needed, minimizing downtime and maximizing the performance and safety of the equipment in use, and balancing the need for rapid response with cost-effectiveness and reliability.

In order to integrate an innovative technology which requires a different framework compared to traditional manufacturing, it is important to understand how the industrialization process for a product is carried out.

2.2 Demand forecasting

In the Aerospace and Defense (A&D) industry, the operational readiness of aircraft and defense systems is vital to maintaining safety, efficiency, and mission success. One critical element in achieving this readiness is ensuring the availability of spare parts through accurate demand forecasting. Leonardo is responsible for anticipating the need for spare parts based on factors such as maintenance schedules, failure rates, and operational needs.

Maintenance schedules are based on regulatory requirements, manufacturer guidelines, and operational needs, with the aim of ensuring the safe and efficient performance of aircraft and defense systems. Maintenance schedules can be divided into two key categories, preventive maintenance and predictive maintenance:

- **Preventive maintenance:** Preventive maintenance involves performing regular inspections, overhauls, and component replacements based on predetermined intervals. These intervals are often determined by usage metrics such as flight hours, operating cycles, or time-based thresholds. By anticipating when specific components will reach the end of their service life or require replacement, Leonardo is able to forecast the corresponding demand for spare parts.

- **Predictive maintenance:** Advancements in sensor technologies and data analytics have enabled a shift toward predictive maintenance, a more dynamic approach to maintenance scheduling. Predictive maintenance leverages real-time data collected from sensors embedded in critical components to monitor performance indicators such as temperature, pressure, vibration, and wear. By analyzing these data, the company can predict the likelihood of component failure before it occurs, allowing for a more accurate forecast of spare part needs. This shift from reactive to proactive maintenance planning not only improves the availability of spare parts but also reduces the risk of unscheduled downtime. Additionally, predictive maintenance helps optimize inventory levels, as parts are only ordered when the condition of the equipment necessitates replacement, rather than relying solely on fixed intervals.

The Customer Support forecasts the volume of hours it needs to allocate to ensure the activities within the programs it is involved in are carried out. When the hours to be allocated exceed the capacity of its internal resources, it is necessary to subcontract a portion of the scheduled activities, limited to those that are non-strategic and non-core, unless there are specific contingent critical issues of competence or contractual obligations.

2.3 Product industrialization

The industrialization of the product is the process of designing and organizing the production of a product that guarantees feasibility and defines the productive system (internal or external, i.e. suppliers) in compliance with the Project requirements, costs, timelines, and quality, ensuring the start of production.

The industrialization process encompasses the necessary activities to:

- Define, plan, and document the production processes for the specific product.
- Design and/or establish the production specifications, as well as develop or acquire the required tools and facilities for the production processes.
- Verify and validate the production processes to ensure their capability to produce consistently and in compliance with the design specifications, while identifying and monitoring potential risks.

Industrialization activities are carried out within the organizational structures of industrial engineering and production engineering, and can be distinctly divided into three key elements:

- **Strategic element**: Defines the phases of knowledge and innovation development required when the technologies and production processes selected for the components/products in question are not already part of the company's existing design and production know-how.
- **Operational element**: Incorporates the design, quality, and cost guidelines and transforms them into manufacturing tools for the development of the aeronautical system, through specialized units.
- **Monitoring and control element**: Oversees the quality management system at the divisional level, ensuring continuous improvement of processes, methodologies, and risk management. This is conducted within the specialized industrial engineering units, fostering the development of know-how among the resources operating within them.

All activities are conducted using standard project management techniques and include:

- Identification of activities (WBS – Work Breakdown Structure) required during all applicable phases of the product lifecycle.
- Matrix linking activities and products (WP – Work Package) and their description (SOW – Statement of Work).
- Definition of timelines and planning.
- Cost estimation and budgeting.
- Monitoring of time and cost performance.
- Management of variances.

The project structures (WBS) and activities (WP) are defined in coordination with the industrial and production engineering units. They are determined by considering the necessary resources (both internal and external) in terms of quantity and competence, in line with planned timelines and budgeted costs.

2.3.1 Product Industrialization - Operational Procedures

The macro-process of product industrialization is composed of the subprocesses described below.

2.3.1.1 Planning and controlling product industrialization. (rif. IND-A-01)

The process, in the field of Industrial Engineering, primarily defines the planning and monitoring of recurring and non-recurring activities of Production Engineering and Industrial Engineering, through the analysis of actual data. Based on this data, the external and internal costs of activities/initiatives that involve the direct participation of the Industrial Engineering Units and Production Engineering are then planned.

2.3.1.2 Conduct the preliminary industrialization study (rif. IND-A-02)

The process involves the development of feasibility studies based on the product's technical specifications, Innovation and Industrialization plans, Technological Development plans, and related customer requirements. These studies are carried out through comparative analyses of similar, existing products and appropriate evaluation 'trade-offs,' framed within the program and/or company budget.

The preliminary industrialization study unfolds through five main phases:

- *Feasibility study*: In the conceptual definition phase, feasibility studies are conducted based on comparative analyses of similar, already developed products, introducing trade-offs to evaluate the best production method and design solution. These are carried out on components and processes selected based on the required design performance (e.g., weight reduction or increased structural characteristics) or cost parameters (e.g., reducing production time or investment in tools and equipment).
- *Planning*: Planning the various phases related to the industrialization process, including capital expenditure (CAPEX) needs and layout; identifying and/or developing Manufacturing Engineering methodologies for the effective and efficient management of the pre-industrialization process. Ensuring that the manufacturing and assembly processes can meet the required production rates while adhering to design specifications.
- *Defining*: Through continuous assessment and monitoring, defining the maturity level of the manufacturing process, identifying any gaps and associated risks, and providing a baseline for the advancement of manufacturing and the management of related risks.
- *Execution*: Performing the activities outlined in the innovation, industrialization, and technological development plans, and generating the associated outputs.

2.3.1.3 Define the processes, methodologies, and systems for the manufacturing area (rif. IND-A-03)

The process aims to pursue innovation and the standardization of work methodologies, operational processes, and supporting IT tools to be used in industrialization activities. Standard methodologies, related documentation, and IT tools are thus defined to guide the product industrialization process.

Across various programs, it also seeks to improve the operational efficiency of the IT systems currently in use within the company, identifying the need for new functionalities both for emerging requirements and new programs.

It also aims to ensure and improve the quality of the databases used in production activities to minimize inconsistencies and variances, and to ensure compliance with technical and economic objectives.

1. Definition of processes, regulation, and assurance of documentation updates for the manufacturing area.
2. Identification of IT requirements and access within IT systems for the manufacturing area.
3. Definition, validation, and dissemination of methodologies, processes, and IT solutions for the manufacturing area.
4. Training on methodologies and IT solutions for the manufacturing area.
5. Monitoring of databases within IT systems for production.

2.3.1.4 Conduct Pre-Planning and Pre-Tooling activities (rif. IND-A-04)

The process involves the preliminary definition and development of all technical and managerial information necessary for a robust internal and external industrial setup, the planning of production activities, the validation of design requirements, and the definition of preliminary material requirements. It also includes identifying potential gaps and risks in the areas, facilities, and production means, as well as in the buy work packages, while monitoring their maturity status and associated application risks.

The process develops through three phases:

1. **Define preliminary material requirements**: This activity involves the preliminary identification of raw, semi-finished, and auxiliary materials to be used during subsequent production phases.
2. **Define the technological process and resources**: This involves identifying the industrial sites where the product will be manufactured, along with the technologies, processes, and materials, including manufacturing and assembly equipment. Make-or-buy analyses are conducted, and product manufacturing structures are designed in line with the assembly sequence definitions, as well as the transportation plan.
3. **Define the production line:** This activity involves the preliminary definition and simulation of assembly lines/cells, as well as the initial layout design for manufacturing and assembly

areas. The described activity aims to establish the operations and sequence that will define the production line, as well as preliminarily size the line in terms of workload and required production rate to identify the necessary type and number of stations. It also involves defining the technical requirements for acquiring and commissioning both the machines and the process plants that constitute the production line. Additionally, the activity includes performing an initial workload balancing of the stations and evaluating a preliminary optimization of the line's efficiency. Finally, it seeks to identify critical issues related to the integration of new machinery or plants into existing production lines.

Particularly relevant outputs of this process are the Manufacturing Plan and the Tooling Plan:

- The "**Manufacturing Plan**" must provide information such as supply status, manufacturing and assembly sequences, interface plans, interchangeability requirements and plans, tooling philosophies, general layouts of assembly/manufacturing areas, production cadences, required production means, as well as industrial processes used, to be adapted, or acquired.
- The "**Tooling Plan,**" under the responsibility of Industrial Engineering, defines the necessary equipment along with the main coordination points with the product components. It should also include preliminary information regarding the assembly and manufacturing tools, which will be useful for developing the technical supply specifications for the equipment.

These activities are developed based on the preliminary information available on the product (e.g., main sections, key interface points between parts and assembly stations), in agreement with the Engineering departments. This type of information enables the anticipation of some work even in the absence of detailed manufacturing and assembly cycles.

2.3.1.5 Conduct the Planning and the Tooling (rif. IND-A-05)

This process immediately follows the conceptual phase, defined as the Pre-planning and Pre-tooling process, and definitively develops all the technical details and technological advancements that were preliminarily developed or initiated in the previous phase. This is done to ensure the industrial manufacturability of work packages, including interchangeable parts and spare parts, by identifying and managing the maturity and risks associated with manufacturing processes through periodic assessments. Below are the activities that comprise the process itself:

1. **Plan and manage the manufacturing product structure:** The detailed Manufacturing product structure, called MBOM (Manufacturing Bill of Material), represents the production bill of materials. It is the "driver" for the activities of production process planning and contains

the product management information necessary for the development of logistics/procurement processes through the input to production scheduling systems and Plant Management systems. The MBOM is the restructuring of the product from the perspective of component or assembly production.

2. **Define and develop tooling and part programs:** This activity consists of defining the detailed technical design requirements for the tooling, which was initially foreseen in the Pre-planning and Pre-tooling phase and overseeing its development. In this phase, the interchangeability plan, defined in the Manufacturing Plan during the previous process, will be detailed with the identification of all tools determining the interchangeable key features, and its update must be ensured throughout the entire life of the Program. The tooling may include manufacturing, assembly, handling, and transport tools, or even part programs (software codes for the operation of numerically controlled machining). The definition and development of tooling and part programs can be carried out internally within the company, by an external supplier, or through a mixed approach involving multiple parties. If it is necessary to use an external supplier, a detailed technical specification will be developed to define all the requirements in support of the procurement and supplier management activities.

3. **Define internal manufacturing cycles:** The work cycles contain the detailed operational instructions necessary for the manufacturing of a part or the assembly of multiple parts, in accordance with process and design specifications, contractual and quality requirements, as well as the supply status. The work cycles are documents that enable the production of a part or assembly by providing a series of descriptive information listed within them, and therefore they:
    - provide the necessary information for the production (manufacturing or assembly) of a part or assembly through the description of the work phases;
    - quantify the labor content required to produce a part or assembly (timing);
    - define the necessary tooling;
    - establish the required materials and/or parts;
    - enable the management of the workflow (progress tracking and cost accounting);
    - allow for the traceability of the part in terms of process, materials, and tooling;
    - support the phase and final inspection/control records for compliance verification purposes.

To allow the monitoring of progress and cost accounting, workflow management is ensured through the breakdown of work activities into phases.

4. **Time the work processes**: This activity aims to determine how much time is spent on various productive and non-productive operations within the work cycles. The measurement of work consists of applying techniques designed to establish the labor content related to a specific task, determining the time required to complete it according to a defined performance standard.

   There are various methods of measuring work. At Leonardo S.p.A. Aircraft Division, the technique primarily used is based on the application of Standard Times. The basic principle is that every elementary movement, when performed by a sufficiently skilled operator, takes practically the same amount of time under the same conditions. This approach involves determining each operation of a work cycle through the following steps:

   1. break down the operation into basic micro-movements (which and how many);
   2. find the appropriate value corresponding to the micro-movements;
   3. sum the values for each of the identified movements;
   4. adjust the values using corrective factors;
   5. determine the standard time for the operation.

   Each micro-movement has a "pre-determined" time value derived from systems like MTM (Methods Time Measurement) / MOST (Maynard Operation Sequence Technique), which are internationally established.

   When the previous technique is not applied, the work measurement is performed using traditional methods based on the knowledge of historical data from similar activities and the evaluators' experience. In this case, the cycle is timed but not standardized. The cycle operation analysis is carried out to assign a specific time to each phase, whether it's a manufacturing or assembly operation, following the standard algorithms present in the company's databases. Based on this data, the methodologist standardizes the cycle timing.

5. **Develop the final production material requirements:** The aim of this activity is to define the correct purchase quantity levels for the production raw materials. Production material requirements refer to the list of materials (raw, standard, purchased parts) needed for the manufacturing of a finished product (aircraft or end-item) or a spare part. The Final Requirement is determined by the dimensional analysis of the parts to be produced and the technologies to be applied, based on the official project drawings received from the

Engineering department of Leonardo S.p.A. Aircraft Division or the Client. Materials that, although contributing to the production of the parts, are not found in the finished product (e.g., auxiliary materials, tooling materials, etc.) are not considered in the requirements.

6. **Develop the final requirement for auxiliary materials:** The aim of this activity is to define the correct purchase quantity levels for materials that support production activities. The development of the work cycles and the definition of the production lines allow for the identification of the materials required for each technological unit to support production, which includes the following macro-categories:
    - *Auxiliary Production Materials:* These are materials that contribute to the manufacturing of parts but are not found in the finished product.
    - *Consumable Auxiliary Materials:* These are materials required for the operation of the facility but do not come into contact with the finished product.
    - *Auxiliary Chemical Materials (production and consumption):* These are substances or articles that, while contributing to the manufacturing of parts, are not found in the finished product (including materials for surface treatments), or substances or articles required for the operation of the facility but do not come into contact with the finished product.

    The requirement for auxiliary materials refers to the initial quantity necessary for the manufacturing of a finished product, a part, or for the maintenance of the equipment/machinery used in the workshops. The initial requirement is determined based on technical documents, workshop tests, and the type of processing, and is established to enable the procurement of the correct types and quantities of materials within the required deadlines.

7. **Define the work packages for external operations**: This activity consists of defining the work packages and processes to be outsourced, based, for example, on the criticalities of the parts, the type of manufacturing and technology, the type of material, and the special processes/critical activities planned in the cycle. The activity develops the technical aspects necessary for the assignment of work packages to suppliers, in accordance with Make/Buy decisions, any Offset requirements, the Work Sharing planned for the Program, and the supplier's demonstrated technological maturity on the product.

8. **Develop layouts and production means:** This activity involves defining the technologies, process plants (hereinafter referred to as plants), and machinery to implement the production

processes established by Leonardo S.p.A. Aircraft Division in light of new programs and/or the development of existing programs, as well as the adaptation of these plants to current laws on health and safety at work. In this context, the development of layouts is intended as the rational, planimetric, and functional organization of the plants and production machinery, as well as the study of handling in the buildings where they will be installed.

The main nodes of the manufacturing product structure, technological processes, assembly sequences, constraints in the selected production areas, and the maximum production rate for which the line is designed are the primary elements that allow detailing the layouts of production areas, identifying areas for docks, production means, warehouses, plants, flow paths, material flow, etc.

To design a layout, it is essential first to understand the product families that will be hosted by the production plant based on the monthly rate agreed upon with the customer. For each family, it is crucial to estimate production volumes and mix, characteristics of the materials used and their handling, the required processes and labor movements. Additionally, possible constraints such as environmental and safety factors, available areas to accommodate the most suitable machines for production, and any machines that could be reused should be duly considered.

Once the information described above is analyzed, it is important to apply general principles that, while considering environmental and safety aspects, can bring economic/investment and flow benefits to the production activity, such as:

- Reducing the number of unnecessary movements and/or operations, finding ways to eliminate them definitively;
- Performing simultaneous movements by combining multiple operations;
- Making movements and operations more comfortable by simplifying methods or working on ergonomic concepts.

A good study for layout development provides flexibility for any subsequent changes and/or "rate increases."

The output of this activity includes the following:

- Layout of production areas;
- Technical specifications for layouts and production areas;
- Definition of production plants and machinery;
- Technical supply specifications for plants and production machinery;
- Supply documents for plants and equipment;
- Test and acceptance reports;

- Process virtual models and simulations;
- Capex Plan.

Once the processes and methods of manufacturing/assembling the product are defined, and its characteristics and requirements are known, the layout of the production areas can be considered frozen. This defines the arrangement of departments and services in the designated area, optimizing available space, material transfer speed, and ensuring as much proximity as possible between cells and production departments with significant interrelationships.

2.3.1.6 Assicurare l'avvio della produzione (rif. IND-A-06)

All activities carried out during the industrialization process must contribute to the realization of the part or assy, object of the process. To ensure that the organization is capable of executing production activities in accordance with established requirements, it is necessary to verify the following:

- The availability and management of approved technical data provided for the execution of the activities.
- The adequacy, in terms of skills and competencies, of the personnel involved.
- The adequacy and availability of equipment and tools that meet the requirements set forth in the approved technical data.
- The identification of necessary materials and appropriate procurement methods that comply with the requirements specified in the approved technical data.
- The minimization of any potential safety risks related to the environment, equipment, and personnel.

Consequently, the final phase of industrialization is the commissioning of manufacturing and assembly lines, which involves completing technological development activities, overseeing the production of the first items to verify the adequacy of the planned, designed, and implemented methods, equipment, materials, areas, and means of production, while identifying and managing the maturity and risks associated with manufacturing processes through periodic assessments (both for internal and external productions).

The technical support activities provided to the workshop during the production of the "First Article," involving the entire production chain (cycles, specifications, equipment, facilities), allow for verifying the adequacy of the entire industrialization process and identifying any necessary modifications.

This phase concludes with the FAI – First Article Inspection: the FAI is the tool used to verify the adequacy of the manufacturing/assembly process, the main equipment used, and the controls performed. It is conducted and/or repeated under the same operating conditions established for serial production to ensure compliance with the applicable technical and quality documentation. The FAI serves as the proof that the entire production process implemented is capable of ensuring the repeatability of the results obtained in conformity with the drawings and specifications, and it is carried out on the first serially produced item.

SAE's International standard EN/AS 9102 defines the requirements for the First Article Inspection and states:

- The definitions of the terms used
- The aspects to consider during FAI activities
- The cases in which a "partial" FAI or a "full" FAI is required
- The management of non-conformities identified during FAI
- The forms to be used and the related completion instructions

The supplier's Quality Control must document the FAI activity using the forms derived from EN/AS 9102, that is:

- Form 1: Part Number Accountability
- Form 2: Product Accountability – Raw material, specifications and special process(es), functional testing
- Form 3: Characteristics accountability, Verification e Compatibility Evaluation

Below are the main aspects to analyze when conducting a First Article Inspection (FAI):

- All characteristics referenced in the drawing must be inspected and recorded.
- It is necessary to verify that all materials used for the production of the part comply with the applicable drawing/specification requirements.
- Tests performed must be verified to ensure they are in accordance with the referenced standards and/or applicable Test Sheets.
- Any special processes and/or Non-Destructive Inspections (NDI) must be highlighted in the process cycle and followed by a control phase with detailed instructions on measurable characteristics (required and recorded). Evidence of their qualification status must be provided. The use of qualified personnel dedicated to specific operational phases identified in the process cycle must also be verified.

- For assemblies, it must be confirmed that FAI has been successfully completed on subassemblies and/or detailed parts.
- The equipment used for the production and/or acceptance of parts must be referenced in the process cycle, indicating the identification code and revision/version; their suitability for the production and/or inspection of the product according to project requirements must be verified and documented during the FAI execution before final release to production.
- A thorough inspection must be carried out on all tools to ensure their correct use and the management/control status (in particular: identification, calibration status, and usage instructions).
- Measuring instruments used for verifying characteristics and identified in the work cycle must be suitable for use, traceable, and in calibrated condition.
- Work cycles and/or work orders must include the identification of the part they refer to and be validated by the supplier's Quality Control. The cycles must be complete in every section, and it must be verified that the required sequence is followed in practice, with phase and inspection attestations including execution dates.
- For all machinery used during the production process that significantly impacts product quality, there must be a performance guarantee from the function responsible for their management. Particular attention must also be given to further verification of certain machinery characteristics, such as precision, wear, and suitability for use before they are employed.

At the conclusion of this phase, there is a handover period during which Industrial Engineering transfers the relevant know-how to the production site. The duration of the handover depends on the complexity of the program and the resources allocated.

2.3.1.7 Monitoring and improving the industrialization of production (rif. IND-A-07)

This process includes all activities following the start of production and the FAI (First Article Inspection) that lead to the improvement of the already completed industrialization. The nature of the activities that may result in a review of industrial processes can stem from program requests or initiatives aimed at addressing recurring issues related to product quality, productivity optimization, and cost reduction.

During the life cycle of a program, the initial industrialization activities may be revisited. Requests for changes can arise from:

- Contractual and commercial developments
- Change in make-or-buy policies
- Product modifications dictated by Technical Egnineering
- Development of new versions/configurations (e.g. special configurations)
- Changes in production rates compared to what was initially planned in the industrialization phase

These factors may lead to a reassessment of existing processes and production systems, and the related reindustrialization, supported by manufacturing risk assessments.

As for recurring improvement initiatives, these emerge from collaboration among the operational functions working in the ongoing program phases. Modifications may result from:

- Root Cause Analysis on productions defects
- Lessons Learned from other programs
- Efficiency data and availability of new machinery/facilities

The initial phases of industrialization will need to be optimized or corrected through improvements in methods and equipment, as well as interventions aimed at enhancing production lines and equipment.

2.4 Off-load of activities to external supplier

Each unit of the Customer Support, in collaboration with the Performance Measurement, Planning & Reporting Unit, which belongs to the Commercial & Customer Services Governance of Commercial & Customer Services, determines the amount of hours to be assigned to third parties (Off-Load) based on Make or Buy considerations, the type of activities, and the mix of required skills. Make components are parts or assemblies that the company manufactures internally, while Buy components are parts or assemblies sourced from external suppliers or vendors.

It is the responsibility of each Customer Support unit to assess the technical/economic risks where they may impact their own Off-Load assigned activities (e.g., fully verticalized activities) and subsequently monitor their progress.

The assignment of activities to external companies is carried out through a supplier selection process and the subsequent issuance of procurement contracts to the selected supplier. These activities must only be assigned to qualified suppliers. The qualified suppliers selected for subcontracting must have the necessary technical expertise to carry out the assigned work package and must possess tools for producing outputs compatible with Leonardo's internal standards.

Based on identified needs, the Customer Support unit requesting the external activity, in accordance with company policies and program planning, issues a Request for Proposal (RdA – Richiesta di Acquisto) for Off-Load work packages, which is then sent to the competent Procurement Function that manages purchases on behalf of Leonardo.

The Customer Support units, to make use of external subcontracting through the assignment of work packages, must prepare and issue the Off-Load request containing the WPS - Work Package Specifications. This document is the means to objectively describe the requirements and, at the same time, identify the service that the Supplier must quote and deliver.

The document contains the following:

- the definition of the product and the work package,
- the Technical, Quality, and Safety requirements to be met,
- the methods and tools to be used described in the work cycles,
- the site where the service must be delivered,
- the schedule of subcontracted activities for the work package, including milestones and responsibilities, identifying those that are the supplier's responsibility and those that are Leonardo's responsibility.

Additionally, the physical and functional interfaces between the company and the supplier are defined, along with all the necessary information for the execution of the work package.

The WPS document must be prepared according to a standard structure, including:

Introduction: This section provides a general description of the product that is the subject of the work package and the context in which it must be integrated. In the case of outsourcing classified activities, it is mandatory to include the references of the classified contract (with Leonardo's client) of which the work package constitutes a subcontract.

References: This section lists the applicable International, National, Company, and Program Regulations for the activity covered by the work package. The company and program regulations are provided to the supplier through the competent Procurement Function. The edition of each listed document must be the latest issued at the date of the contract signing, unless otherwise specified. In the event of regulatory updates during the contract period, it will be the responsibility of the requesting unit to provide any necessary updates to the competent Procurement Function for forwarding to the supplier.

Abbreviations and Definitions: This section lists all the abbreviations and acronyms used in the document along with their meanings, as well as the definitions of specific terms found in the text.

Subcontracted Product: In this section, divided into four paragraphs, a description of the work package is provided, defining the objectives and criteria that must be met in terms of both content and the tools to be used for the development of the product being subcontracted.

1. **Input Data**: This section provides a comprehensive description of the input data that are strictly necessary for the supplier to carry out the work package, identifying the documentation that contains them and the methods by which Leonardo transfers them to the supplier in accordance with applicable security regulations.
2. **Contents**: This section provides a detailed description of the product to be developed, along with the quality requirements to be referenced, as well as the breakdown of activities by contract within the required timeframe. Any specific requirements of the subcontract can be detailed, if necessary, in documents attached to the WPS itself. The requirements and standards (whether Company or external) applicable to the work package must be as comprehensive as possible. It must always be specified that the supplier may not apply requirements or use standards other than those explicitly provided in Leonardo 's WPS.
3. **Deliverables**: This section must identify the deliverables related to the work package and define, in accordance with the applicable reference documents, the methods for the release, transfer, and acceptance of the deliverables themselves.
4. **Product Configuration Management**: This section defines the requirements for the supplier in terms of Configuration Management, specifying management methods and systems, data exchange procedures, periodic reporting requirements, and methods for managing changes to the contractual baseline. Additionally, any warranty terms required for the supply must be identified in this section.

Activity Management and Responsibilities: This section must specify the location where the activities will be carried out. As a general policy, Off-Load activities will be performed at the supplier's site. In special cases related to the nature of the work package activities, such as the need for specific tools or facilities, it may be arranged for the activity to be conducted at Leonardo premises; in such cases, it must be specified to what extent the supplier will operate outside their own site.
In both cases, the following must also be indicated:

- *Leonardo - Supplier Interface*: managerial and organizational interfaces between Leonardo and the supplier. In particular, Leonardo and the supplier must identify their respective points of contact, responsible for coordinating the specific work package within their respective organizations, and who alone are entrusted with managing the official interface between Leonardo and the supplier.
- *Responsibilities*: This section establishes the responsibilities assigned to Leonardo and those attributed to the supplier. Specifically, it must always be clearly indicated what level of signature the supplier is authorized to affix to the issued outputs, as well as the methods by which the Leonardo unit responsible for the work package approves or authorizes these outputs.
- *Professional level of the resources*: This section must indicate the activity required from the supplier and accurately describe the professional level of the resources needed to perform the activity, in terms of technical skills/specialization, required general and specific experience, required knowledge of HW/SW tools, required foreign language proficiency and at what level, need for specific training to perform the activity, the organizational level required from the supplier.

Subcontracting Schedule: This section specifies the schedule of activities for the development of the work package, identifying the supply milestones. It will also indicate how the supplier must prepare and maintain an updated detailed schedule of the subcontracted activities. The supplier must initially communicate this schedule during the offer phase (including volume estimates and resource planning) and subsequently agree on it with the requesting unit. Additionally, the supplier is required to periodically provide, at an agreed frequency with the WP Leader of the work package, a status report on the actual progress of the activity as a percentage relative to the contracted theoretical progress requirement.

Review: In this section are reported the methods for conducting Technical Reviews between Leonardo and the Supplier, convened through their respective interfaces, are established during the execution of the work package activities. If applicable, in addition to the Technical Reviews, Design Reviews (Supplier or Supplier/Leonardo) will also be conducted.

Facilities and HW/SW tools: This section specifies the methods, systems, facilities, and equipment necessary for the execution of the work package, indicating which are provided by Leonardo and which are the supplier's responsibility. Among other things, the necessary Hardware and Software tools required by the supplier for the development and execution of the assigned work package must be specified. It is important to note that in the case of Hardware brought by the supplier to Leonardo premises with access to the company network, except for the case of external consultants working remotely (smart working), it must remain within the workspace for the entire duration of the contract and can only be removed at the end of the collaboration period stipulated by the order, after being stripped of any information regarding the work performed.

Supplier Quality Plan: The level of detail with which the Quality Plan must be issued should provide evidence of how the supplier intends to meet all the requirements expressed by Leonardo. The Supplier's Quality Plan, issued even in a preliminary form during the offer submission phase, must be subject to the joint approval of the CSS&T Quality & Process Improvement Unit, Supplier Qualification, and the requesting unit. In the case of a first-time qualification, it will also be evaluated by the relevant Quality Assurance and Certification organizational unit. It will be the responsibility of the WP Leader from the requesting unit of the work package to forward the Quality Plan for approval to the aforementioned units, once received from the supplier. In the case of carry-over work packages (i.e., work packages that integrate activities previously assigned to the same supplier), it will be sufficient to request an update of the previously approved Quality Plan from Leonardo.

Safety Aspects and Trade Compliance Aspects: Within the WPS, it is necessary to specify the security requirements regarding the data to be handled by the supplier's personnel and the areas to which such personnel must have access. It should inform the supplier and the Leonardo Security Unit of the security aspects of the work package, including:

- Secrecy/Confidentiality Classification of the Activity
- Secrecy/Confidentiality Classification of the Work Environment
- Secrecy/Confidentiality Classification of the Resources

2.5 Technical Management of Spare Parts Offers

The supply flow of spare parts is initiated by the customer, who requests a replacement material from Leonardo to meet a specific need through the issuance of an RfI/RfQ (Request for Information/Request for Quotation). The processes are divided into two types:

- **Initial Provisioning**: Initial supply related to the sale of the aircraft.
- **Re-provisioning**: Supply related to a specific customer need that arises after the sale.

Within this distinction, there are two different types of logistical management for the supply, summarized as follows:

- **Consignment Sale**: The customer is supplied through a sales process that involves an immediate transfer of ownership upon receipt/shipment, triggering invoicing. The request can be made under an already established contract between the parties or on a "Case by Case" basis, typically in urgent situations (e.g., AOG – Aircraft On Ground events).
- **Consignment Stock**: There is no transfer of ownership at the time of physical delivery of the goods to the customer. Ownership is transferred once the customer declares consumption (i.e., when the customer takes charge of the goods).

The sale of supplies is also managed through **Drop-Shipment**: when the customer places an order, Leonardo forwards it to a third-party supplier who directly manages the logistics and shipment. The Drop-Shipment model is generally used for "Case by Case" sales and emergencies (such as AOG events).

2.5.1 Technical Management of Spare Parts Offers – Operational Procedures

The spare parts management process of the Aircraft Divisioni s structured into the following macro-phases:

1. Receipt of RfI/RfQ and creation of sales documents
2. Technical Vetting
3. Identification of the Type of Procurement (“Tipo Approvigionamento” - TA) for the part
4. Issuance of the Technical Vetting report
5. Internal Request for Quotation
6. Generation of demand and evaluation
7. Definition of Lead Time
8. Quotation and costs
9. Consolidation of the offer quotation and economic evaluation
10. Issuance of Offer

2.5.1.1 Receipt of RfI/RfQ and creation of sales documents

The designated commercial representative, upon receiving an RfI/RfQ or an order request from the customer for spare parts supply or repair, uploads the list of requested Part Numbers into the company's ERP system and requests Engineering to verify the presence of the parts in the Applicability Catalog. The Applicability Catalogs contain the list of materials associated with a specific customer/program/model and are used to perform applicability checks on the sales documents. If there are blocked positions, meaning parts that are not present in the relevant Applicability Catalog, a technical/configurational validation is required.

2.5.1.2 Technical Vetting

Technical Vetting is the process of technical and configurational validation of customer requests for quotes and procurement orders for spare parts. Verifications are performed on the materials referenced in the sales documents within the company's ERP system.

Materials may be blocked if they are not listed in the Applicability Catalog. In such cases, after confirming that the material is applicable to the aircraft's in-service configuration and that the spare part is valid, it is added to the Catalog along with the relevant data.

If a part is found to be obsolete, meaning it can no longer be supplied by external vendors or Leonardo's operational units, the issue is reported to the department responsible for obsolescence management. This department will collaborate with engineering to initiate the process of finding alternative solutions.

2.5.1.3 Identification of the Type of Procurement ("Tipo Approvigionamento" - TA) for the part

The TA (Type of Procurement) is a classification code that indicates whether a Part Number is produced internally within Leonardo S.p.A. facilities, produced externally (through subcontracting), partially produced externally and completed internally, or purchased as a finished product. It also specifies whether the raw material is to be sent to the supplier.

Upon receiving the list of requested parts, the ERP system is checked to determine which facilities have procurement data for those Part Numbers, in order to identify the correct one based on the most recent production and/or purchase orders issued.

Defining the TA at this stage allows for assigning a value to the requested parts.

2.5.1.4 Issuance of the Technical Vetting report

Once the procedures for applicability and technical/configurational validity verification are completed, the validation of the sales documents is communicated to the responsible commercial representative. The following information is provided to them (based on availability and the relevant program):

- Qualified Part Numbers
- Manufacturer Code
- Manufacturer name
- Part classification (safety critical, mission critical, non-critical)

- Lead Time
- Shelf life (i.e. period during which the part can be stored under specified conditions without becoming unsuitable for use)
- Quantity
- Make or Buy
- TA
- Competent facility

It is important to emphasize that the Make/Buy, TA, and Lead Time data are provided with the understanding that they are only indicative and not necessarily accurate, as they are derived from the data available in the ERP system. Therefore, it may happen that during the quotation phase, after the Technical Vetting, a part initially identified as "Buy" is actually a "Make," or vice versa. These cases will be identified afterward, and the data in the company's management system will be correctly updated.

Regarding Lead Time, after the issuance of the Technical Vetting report, it will be confirmed or corrected by the responsible buyers for "Buy" parts or by the production logistics departments of the various facilities for "Make" parts.

2.5.1.5 Internal Request for Quotation

After the issuance of the Technical Vetting report, the cost estimation process is initiated. To calculate the costs related to spare parts, for "Buy" parts, the responsible buyers are engaged to issue requests for quotations to Leonardo's suppliers. For the cost estimation of "Make" parts, databases are used to search for historical data related to the materials in question. If a prior evaluation is not already available in the proprietary databases, a detailed estimate is developed, including non-recurring costs, recurring costs, material costs, and lead time.

2.5.1.6 Generation of demand and evaluation

The responsible unit of Industrial Engineering, utilizing the previous analysis performed on the TA, conducts a search in the company's ERP system and extracts the multi-level composition of the Part Number from the relevant plant. From this, the following elements are filtered to generate an external order:

- Raw Materials
- Standard Materials
- Equipment
- Partial external parts

- Complete external parts
- Purchased parts

2.5.1.7 Quotations and costs

The cost estimations follow different workflows depending on whether they are Purchased Parts or Manufactured Parts.

Purchased Parts:

- Estimation is based on historical supplier data adjusted to the current year's economic conditions or on quotes requested ad hoc.

Manufactured Parts:

- **External Make (outsourced)**: Estimation follows the same process as for purchased parts.
- Internal Make:
    - Provision of standard data for recurring hours, as well as any non-recurring hours and costs.
    - Provision of raw material and standard material requirements.
    - Valuation of material requirements and application of Material Handling costs according to the current year's economic conditions.
    - Valuation of labor hours according to the current year's economic conditions.
    - Calculation of Lead Time.

Periodically, the economic parameters used for material valuations, material handling application, and labor hours are updated to reflect current conditions.

2.5.1.8 Consolidation of the offer quotation and economic evaluation

The Costing Consolidation unit generates a single consolidated quotation document, based on constant economic conditions, which includes quotes for both make and buy parts, as well as lead times, in alignment with the customer’s request. This document is then sent to the relevant commercial office.

2.5.1.9 Issuance of Offer

The commercial office managing the contract, based on the cost estimate received, the economic conditions, and the requesting customer, prepares the commercial offer and submits it to the customer.

2.6 Technologies for the production of spare parts: Casting, Forging, and Machining

In the A&D industry, the production of spare parts requires robust, high-performance manufacturing techniques to meet stringent standards for safety, reliability, and durability. Among the most used technologies are casting, forging, and machining. Each method offers unique advantages and faces specific challenges, making them suitable for different applications depending on the material requirements, production scale, and functional demands of the part.

2.6.1 Casting

Casting is a formative process in which molten metal or material is poured into a pre-shaped mold, allowing the material to cool and solidify into the final part. This technology is particularly advantageous for producing complex geometries, intricate shapes, and large components in a cost-

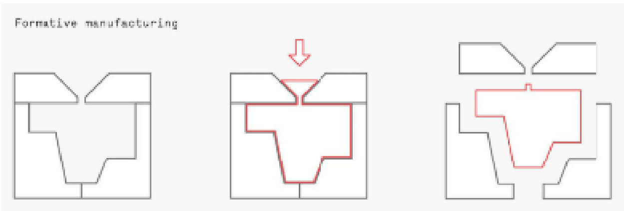


Figure 6: Formative process

effective manner. Casting is widely used for non-critical aerospace parts such as housings, brackets, or turbine casings, where precision is important but not the most critical factor. It is also efficient for mass production due to the ability to reuse molds, reducing overall production time. However, cast parts often face challenges in terms of material properties. Due to the nature of the process, cast components can suffer from porosity, internal voids, or micro-cracks, which can weaken the structure, limiting the use of casting for highly critical or load-bearing aerospace components.

2.6.2 Forging

Forging usually involves shaping metal under extreme pressure and heat, resulting in a denser, stronger structure than one obtainable with a casting process. The forging process aligns and refines the metal's grain structure, improving its mechanical properties, including strength, toughness, and fatigue resistance. Forged components are commonly used in the production of parts that require high durability and can withstand substantial stresses, such as landing gear, engine components, and turbine blades. The primary advantage of forging is the increased strength of the final product, making it ideal for critical applications in both aerospace and defense. However, the high tooling costs and the complex nature of the process limit its use to parts with relatively simpler shapes. Additionally, the requirement for high-temperature processing and specialized equipment adds to the overall expense and limits its scalability for more intricate designs.

2.6.3 Machining

Machining is perhaps the most precise method for producing aerospace and defense spare parts. It involves removing material from a solid workpiece using cutting tools to achieve the final shape, size, and surface finish of the component. Machining offers the highest levels of accuracy and precision, making it essential for parts that require tight tolerances, such as engine components, fasteners, and control systems. Aerospace and defense components often demand machining for critical parts where even slight deviations in dimensions can compromise the performance and safety of an aircraft or military system. Despite its precision, machining has notable drawbacks. The process can be material-intensive, as much of the original workpiece is discarded as waste. This increases both material costs and environmental impact. Additionally, machining complex geometries often requires multiple operations, which can lead to longer production times and higher labor costs, making it less efficient for large-scale production compared to casting or forging.

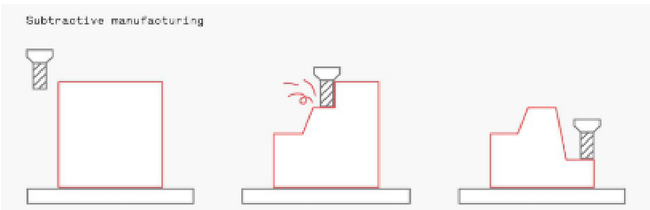


Figure 7: Subtractive process

Casting, forging, and machining each play critical roles in the manufacturing of aerospace and defense spare parts, with distinct advantages, limitations, and cost implications. Casting is generally the most cost-effective for mass production, especially for large or complex parts, due to its ability to reuse molds and minimize material waste. However, additional costs may arise from quality control, as cast parts often require inspection and potential rework due to defects. Forging tends to have higher upfront costs due to the need for specialized equipment and tooling, but it produces stronger, more durable components, making it cost-effective for high-stress parts in critical applications where long-term reliability is paramount. While machining offers unparalleled precision, the process is often the most expensive per part due to significant material waste, time-consuming operations, and the labor-intensive nature of machining intricate components. Additionally, machining may involve higher raw material costs since larger workpieces are required to account for the material removed during processing. Ultimately, the choice of technology depends on the balance between production scale, precision requirements, and cost, with hybrid approaches increasingly being employed to optimize both performance and efficiency.

2.7 Challenges and limitations of traditional manufacturing technologies

Traditional manufacturing technologies, such as machining, casting, and forging, have been the backbone of production in the Aerospace and Defense sectors for decades. While they offer high repeatability, precision, and compatibility with established materials, these technologies face significant challenges when applied to the complex and evolving needs of modern aerospace applications.

One major limitation is the significant lead time associated with traditional manufacturing processes. Machining and casting, for example, require extensive setup, including tooling, mold creation, and programming of CNC machines, which can result in long production timelines. This delay is particularly problematic for the production of spare parts, where urgent demand for critical components cannot be met efficiently through conventional methods. Additionally, these technologies often require centralized production facilities, creating supply chain dependencies that can lead to delays and increased costs for inventory management and transportation.

The Aerospace and Defense industry is also subject to stringent regulatory requirements, which further constrain the availability of production sites. Compliance with standards such as AS9100 and NADCAP is essential, but it limits the number of facilities that can legally manufacture aerospace-grade components. This restriction can create bottlenecks in production, as parts may need to be manufactured in a limited number of certified sites, leading to longer lead times and potential delays in meeting demand. The concentration of production in fewer facilities also increases the risk of disruptions, making the supply chain more vulnerable to local issues such as labor shortages or equipment failures.

Another notable challenge is the lack of flexibility in design. Traditional manufacturing methods are constrained by the limitations of molds and cutting tools, which restrict the ability to produce complex geometries or make iterative design changes without incurring high costs. This inflexibility poses obstacles when trying to innovate or customize parts for specific applications, a common need in Aerospace and Defense sectors where parts may require unique adaptations for different operational contexts.

Traditional technologies are usually resource-intensive. Processes like subtractive machining generate substantial material waste, as parts are carved from larger blocks of material, often with low buy-to-fly ratios. For instance, producing a component via machining may involve cutting away up to 90% of the original material, leading to increased material costs and environmental impact. This inefficiency contrasts with additive manufacturing, which builds parts layer by layer, minimizing waste and offering more sustainable alternatives.

Finally, traditional manufacturing technologies struggle with adaptability, particularly when supporting long product lifecycles, as is common in Aerospace and Defense. As components and materials evolve, traditional manufacturing often lacks the agility to quickly adapt to new requirements, posing a risk of obsolescence for both parts and production equipment and limitations for long-term performance improvements.

Overall, while traditional manufacturing technologies provide well-established production methods, they are increasingly challenged by the demands for rapid production, flexibility, regulatory compliance, waste reduction, and adaptability—factors that underscore the potential advantages of integrating additive manufacturing solutions.

CHAPTER 3: ADDITIVE MANUFACTURING

3.1 Introduction

Additive Manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology in various industries, including aerospace and defense. In opposition to traditional subtractive manufacturing methods, which remove material to create parts, AM builds components layer by layer from digital models, enabling the production of complex geometries that were previously difficult or impossible to achieve. This technological advancement offers significant potential for the aerospace and defense sectors, where the demand for lightweight, high-strength, and customized components is paramount. The key feature of the technology that makes it relevant for the A&D sector is flexibility: with a single machine a lot of variety of parts can be produced, and the drastic reduction of necessary tooling (molds) allows for rapid prototyping. This means that starting from CAD, a single machine can produce a lot of different geometries rapidly and economically.

As the aerospace and defense industries face increasing pressure to innovate while minimizing costs and lead times, the integration of AM into the manufacturing of spare parts as well as the production of GSE presents a compelling business opportunity.

Leonardo Aircraft Division will integrate solutions for spare parts manufacturing on-demand and on-time, leveraging on Additive Manufacturing technologies, in order to:

• Speed up spare parts delivery

• Shorten AOG and AOCP events

• Reduce dependence on suppliers

• Reduce inventory

• Improve logistic support

• Optimize resource allocation and decision-making

• Save material, energy and costs

• Enable design optimization

• Trigger customization

• Particular attention will be paid to regulation, certification and airworthiness issues associated to introducing such innovative (and disruptive) approach to Customer Support and Services.

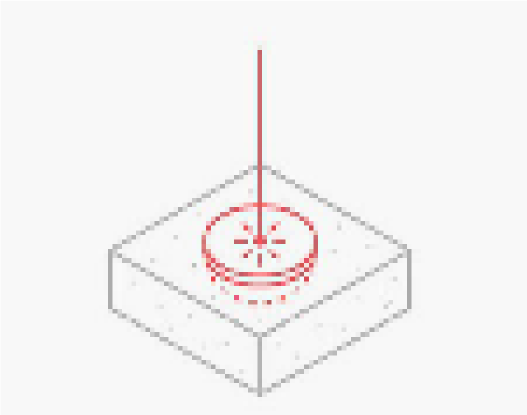
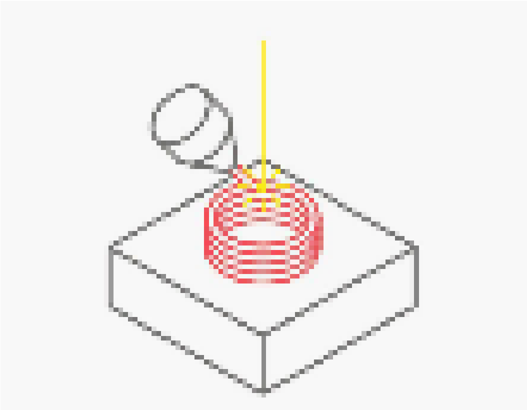
3.2 Additive Manufacturing Process and Technologies

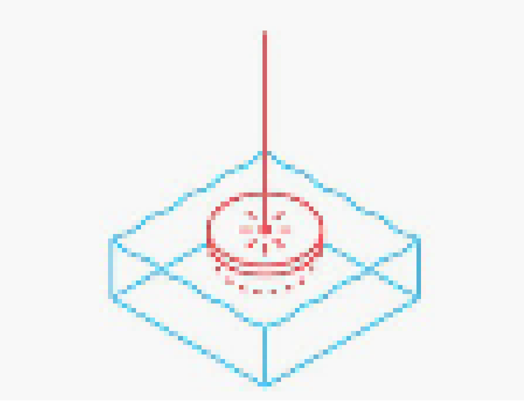
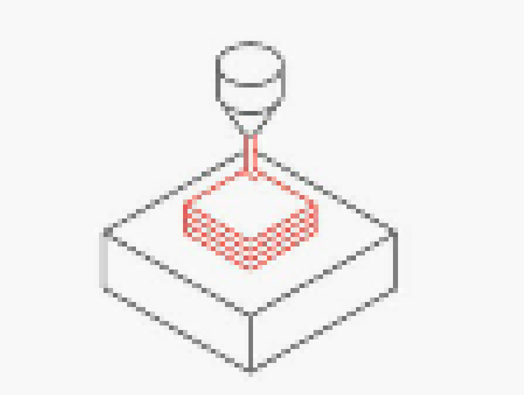
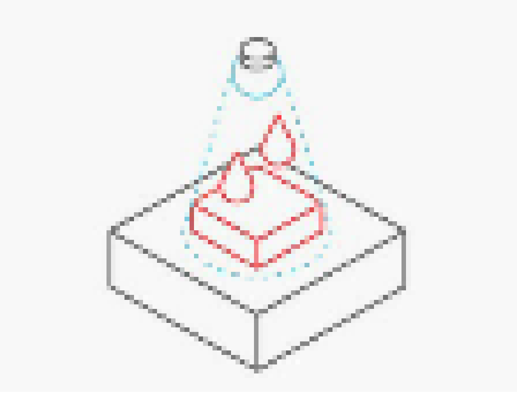
Additive Manufacturing (AM) is a process used to fabricate objects from 3D computer models (CAD models), where the production of an object occurs through the successive deposition of various layers of materials [1]. It is a manufacturing concept that contrasts with the more traditional subtractive manufacturing. Subtractive manufacturing consists in removing an excess of material from a starting workpart so that what remains is the desired final geometry. Conversely, Additive Manufacturing consists in adding and joining material only where it is needed to obtain the part.

The process is composed of:

- *CAD file*: The 3D computer model of the component to be created is generated.
- *Numerical Slicing*: The component is divided into layers that will then be constructed one after the other by the machine.
- *Layer Processing*: The operator utilizes the machine's software to set up the construction path for the components.
- *Layer by Layer Manufacture*: The machine deposits and processes one layer of material after another to build the component.
- *Final Component*: After the in-machine process and finishing operations, the final component is obtained.

ISO standard ASTM 52900 defines rigorously process categories, data, materials, applications, and properties. Each technology has distinct capabilities, making it suitable for different applications based in particular on material requirements, mechanical properties, production volumes costs, infrastructure, etc. Process categories are listed as seven different types:

Power Bed Fusion (PBF): process in which thermal energy selectively fuses regions of a powder bed. A power bed is defined as a build area in an additive manufacturing system in which feedstock is deposited and selectively fused by means of a heat source or bounded by means of an adhesive to build up parts	
Direct Energy Deposition (DED): Process in which focused thermal energy is used to fuse materials by melting as they are being deposited	
Binder Jetting (BJT): process in which a liquid bonding agent is selectively deposited to join powder materials	

Vat Photopolymerization: process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization	
Fused Filament Fabrication (FFF): process in which material is selectively dispensed through a nozzle or orifice	
Multi Jet Fusion (MJF): process in which ink jet heads are used to deposit fusing and detailing agents onto a bed of powdered thermoplastic material, typically nylon, before applying thermal energy to fuse the layers together.	

Opportunities:

- Rapid prototyping
- Freedom of design/material
- Design for AM and Topological optimization
- Complexity and customization
- On-demand flexible production

- Low lead, production and turn-around time

Limitations:

- Hardly turn-key solution
- Post-processing often needed
- Parts conformity
- Lack of certifications and standards
- No economies of scale
- High investment cost

It is worth noting that the lack of economies of scale is majorly due to the capability of AM to manufacture without expensive tooling, that with traditional technologies is amortized among the parts produced. 3D printing is most appropriate for the on-demand production and is advantageous for the production of few highly complex and/or customized parts.

On one hand it can be used to produce complex and optimized aircraft components, allowing in particularly rapid prototyping and testing, and to optimize the design of parts to save weight, material and increase performance.

On the other hand, AM can be used to produce spare parts on-demand and on time, possibly in strategic locations as close as possible to the end user.

3.3 Materials

The two major categories of AM materials are polymers and metals. A variety of filled and composite materials are also available, as well as ceramics and cermets (ceramic-metal hybrids) but those are out of the scope of this thesis. Examples include materials used as patterns for investment- and sand-casting applications.

Many polymer options are available for AM, but offerings are small compared to those for conventional processing. AM materials may be selected based on tensile strength, rigidity, biocompatibility, glass transition temperature, color, and transparency. Additional properties include moisture resistance, sterilization, fire retardancy, and smoke and toxicity emissions. Materials range from hard and stiff to soft, rubber-like elastomers.

Polymers are classified into two groups based on their behavior at high temperatures. Thermoplastics can be repeatedly melted, cooled, and solidified. They retain their properties, although some degradation can occur, particularly with repeated high-temperature exposure. Thermoset polymers are permanently cured once they are polymerized. After polymerization, thermosets do not melt. Photopolymers, like those used in VPP and MJT, are liquid thermoset resins that are polymerized when exposed to certain wavelengths of light.

Materials used in FFF systems are almost exclusively thermoplastics, such as ABS, polycarbonate (PC), PC/ABS blends, polyamides (PA), and PLA. 3DXTech and Stratasys offer ULTEM 9085 and ULTEM 1010. These thermoplastic polyetherimides have a high strength-to-weight ratio and good fire, smoke, and toxicity properties, making them well suited for the aerospace industry.

When printing a metal part, there is a relevant range of materials from which to choose from:

- Steels
- Titanium
- Titanium alloys
- Aluminum alloys
- Nickel-based superalloys
- Cobalt-chromium superalloys
- Copper alloys
- Gold
- Silver
- Platinum
- Palladium
- Tantalum
- Tungsten
- Niobium

The choice is not limited to this list and AM providers are always researching for new metals and alloys adaptable for additive production. Many of these materials have been available for some time, but their use for final part production has been limited. This is mainly due to qualification and certification requirements in aerospace. Over the last few years, some companies have qualified/certified specific alloys. This is a necessary step in the adoption of metal AM in highly regulated industries. For example, Burloak Technologies certified an AlSi10Mg alloy to Boeing's BAC 5673 specification. Leonardo as well has emanated four NTAs ("Nota Tecnica Aziendale") relevant for AM:

- NTA75779 establishes procedures, requirements, and inspections for the manufacture of parts in thermoplastic material with Fused Filament Fabrication (FFF) process.
- NTA62911 establishes the requirements for the filament materials used to fabricate components by FFF process according to NTA75779.
- NTA55952 covers additively manufactured titanium-6aluminum-4vanadium (Ti6Al4V) components using full-melt Power Bed Fusion (PBF) such as electron beam melting and laser melting.

The preparation and emanation of an NTA is expensive and time consuming. The fact that LAD, as well as other companies in the industry, has qualified materials and processes for internal AM production underlines the commitment of the industry in implementing the technology.

There are notable material differences between additive manufacturing of metals and plastics, which influence the mode of application of these technologies in different scenarios. The first key distinction lies in the costs: metal printing technologies are not only considerably more expensive but also require highly qualified operators and specialized facilities, such as dedicated storage rooms for metal powders. The second major difference is in the criticality of the parts produced. Plastic components are typically non-safety and non-mission critical, as shown with the tool in Figure 1, although damage to these parts can cause inconvenience to operators. However, in some cases, the failure of plastic parts can have a more disruptive effect, such as with cockpit buttons, as illustrated in Figure 2.

[FOTO DI PARTI IN PLASTICA E PULSANTIERA COCKPIT]

3.4 Pre-Processing and Post-Processing

The three basic steps in the AM process are pre-processing, printing, and post-processing. Pre-Processing activities are those activities required before the build phase starts (i.e. model repair, build orientation, part nesting, build preparation, etc.), Post-processing encompasses all manufacturing activities that occur from the time a build is complete to the time the part is used (i.e. support material removal, cleaning, heat treatments, surface treatments, etc.). Wholers Associates completed a survey in 2021 where AM service providers where asked what proportion of their part costs are attributed to pre-processing and post-processing compared to the build phase: post processing activities accounted for 28.6% of costs for metal parts and 24% for polymer parts. The results of the survey are summarized in the table: [SOURCE: WHOLERS]

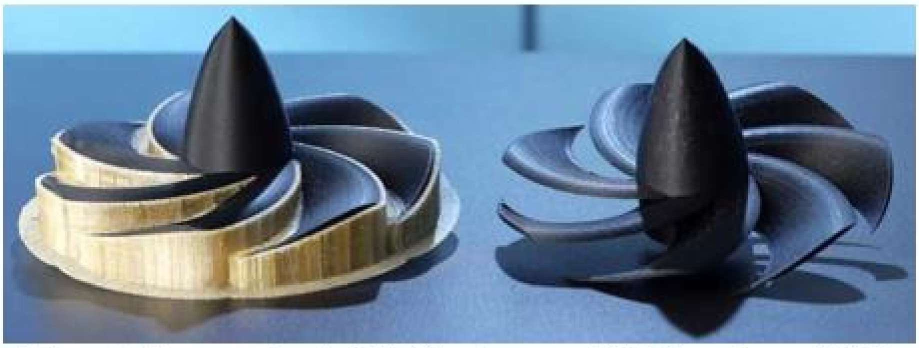
	Metal	Polymer	Both
Pre-processing	10.2%	12.4%	10.2%
Printing	61.2%	62.9%	62.5%
Post-processing	28.6%	24.7%	27.3%

For the production of spare parts in the aerospace industry and specifically within Leonardo Aircraft, Fused Filament Fabrication (FFF) for polymers and Power Bed Fusion (PBF) for metals are the most relevant AM technologies to be considered, so in the next paragraph the pre- and post- processes for these two are examined.

3.4.1 Polymers Part – Fused Filament Fabrication (FFF)

The first step for any manufacturing process is to check the quality of the manufacturing files and data and to repair those if necessary. Then the job is prepared in software by arranging parts on the build platform (nesting) and generating support structures: these can be designed by an engineer or generated with the aid of specific software such as CURA®. Before the manufacturing process starts, the build plate of the 3D printer is cleaned, and the build chamber is preheated at the appropriate temperature.

After being removed from the build chamber and the build plate, supports are removed. Supports are structures printed during the manufacturing process necessary to anchor a part to its build platform. The removal of support structures is often a manual process since most FFF systems build both the part and the support structures from the same material, but there are some FFF systems that instead print with soluble support material: this can be dissolved using a solution (often combined with ultrasonic washing) and it is advantageous for fragile structures that might be damaged if supports were removed mechanically.


Water-soluble support material (left) and removed (right), courtesy of Infinite

Most AM parts require also a surface finishing to achieve the desired results. Depending on the features and usage of the part considered, it could be necessary to achieve an exceptionally smooth surface: this means removing all “stair steps” inevitably caused by the layer-by-layer process and eventual imperfections left from the removal of the support structures. Vapor treatment is a process that smooths the surface of a part with vaporized solvents. It is particularly suitable for complex geometries because it does not require part-specific tooling, but the process requires great care and precise timing because the part is being dissolved during vapor treatment so dimensional accuracy could be impacted.

If an engineering-quality surface finishing is required, manual or CNC machining may be the only way to achieve it. The machining process is the same as with any other polymer machining, although care must be taken due to weakness in of the part the build direction.

3.4.2 Metal Parts – Power Bed Fusion

Considerable post-processing is usually required before metal AM parts are ready for the intended application. Part design and pre-processing must include considerations of the surface area where post-processing and finishing are required. Also, determining the type and location of the support structures is a critical prebuild step considering that the surface where supports are removed is rough and will likely need more finishing: if a surface needs a machined tolerance, it can be advantageous to make it the supported surface in order to minimize finishing time. Supports are more critical for parts built on laser PBF systems than on electron beam systems, but this technology leaves the powder surrounding the part partially sintered and needs to be removed, usually with abrasive blasting.

With metal AM, residual stress is unavoidable. Metal PBF may be considered as microwelding, and the residual stresses are the result of the rapid heating and cooling of the small melt pool surrounded by solid metal. The melt pool solidifies and contracts as it cools in the solid state. This contraction is greater than that of the cooler underlying material, resulting in residual stress that over hundreds or thousands of layers can be sufficiently widespread and can be substantial enough to bend a build plate. So after the parts are cleaned from excess powder, they go through a stress-relieving thermal process to prevent warping and reduce internal stress, usually with the parts and supports still attached to the build plate. For most aerospace spare parts, where high-performance materials are required, hot isostatic pressing (HIP) is required. HIP is a treatment used to improve the material properties by applying high temperature and pressure uniformly to remove porosity and cracks. The process involves placing the part in a high-pressure, high-temperature environment, typically using a pressurized inert gas like argon.

Supports are removed after the thermal stress relief. Parts and the support structures are initially welded to the building plate and needs to be removed. This is generally done with Electrical Discharge Machining (EDM), a bandsaw, or multitool.

All metal AM parts have some measure of surface roughness: laser PBF processes commonly produce as-built surfaces of about 15.2 μm roughness average (Ra) on the top-facing and vertical surfaces. With GE Additive's electron beam process, the surface finish can be 20.3-25.4 μm Ra for top and vertical surfaces. Down-facing surfaces, and surfaces where support material is attached, are often substantially rougher and can have 1,000 μm Ra or worse. Most aerospace parts have more stringent requirements, so a surface finishing is needed. The processes that can reduce surface roughness of metal AM parts can involve mechanical action (i.e. shot peening and machining) as well as chemical actions (i.e. electropolishing).

Shot peening is a microhammering process that flattens tiny peaks on the part surface by hitting that surface with small steel ball bearings. It has a forging effect on the part that both smooths and hardens the surface.

Machining an AM metal parts is the most reliable activity applicable in order to meet the engineering tolerances for aerospace parts. Machining an AM part is no different from machining any other mechanical part, but often mounting complex parts in a CNC machine can take longer than the machining itself: it can become important to add fixtures and mounting points to a part design to facilitate mounting operations.

Post-processing can represent up to 40% of the total cost to produce an AM part and poses relevant threats to the adoption of the technology: if machining is needed for the finishing of a part, the transportations required to bring the part to qualified suppliers could generate a bottleneck and offset the advantages of producing Just-In-Time and in place.

3.5 Reasons for integrating Additive Manufacturing in the supply chain

Additive Manufacturing becomes a candidate for final part production when it adds value compared to parts made by conventional manufacturing processes. The building of the part through additive manufacturing, as of today, can be considered far more costly than conventional manufacturing processes, but AM can affect key aspects of the product development process and manufacturing so that overall, it can become convenient for the company in some cases. The next paragraphs give a overview of the key aspects of benefits of AM compared to traditional technologies.

3.5.1 Reduction of tooling

AM does not require tooling to produce a part: a 3D printer can virtually manufacture any geometry without any dedicated physical tool. Usually, molds for casting and tools for machining are manufactured with subtractive manufacturing themselves. The removal of the need of tools can drastically reduce lead times, costs, and a product's time to market. Furthermore, all the effort related to the management and storage of tools is erased as the risks related to failures of those parts.

3.5.2 On-demand manufacturing: reduced lead time, inventory, and transportation effort

One unique feature of AM is that a single production system can manufacture a wide range of spare parts that, without this technology, need instead a collection of different manufacturing technologies, often spread around the network of suppliers.

Aircrafts are made up of tens of thousands of unique parts and fabricating, tracking, and storing those is costly. Transporting the parts to and from a storage warehouse and to and from suppliers and client can become a bottleneck. Printing a spare part as needed and where it is needed (or in a location close to) from a digital inventory has the potential to eliminate or drastically reduce storing necessities. In some instances, it would be possible to transmit digital files and print at the point of service, eliminating the transportation efforts.

3.5.3 Part consolidation: reduced inventory and weight

Production with additive manufacturing allows the reduction of assemblies: many parts can be consolidated into one. Reducing the number of parts in an assembly immediately reduces the overhead cost and time associated with documentation, inspection, and product planning and control. Also, reduced part count results in reduction of time and labor to assemble the product.

When GE aviation analyzed its CT7 helicopter engine, it determined that about 40% of the engine could be manufactured using AM. A subsequent redesign spanning 8 months consolidated 900 parts into 16. The resulting weight was reduced by 35%. Reducing the weight of a component that maintains the same mechanical properties is going to reduce operational costs for the life of the components: fuel consumption for part in service is reduced and, considering an aircraft's life cycle, this reduction is relevant.

3.5.4 Waste reduction: buy-to-fly ratio

Most aerospace spare parts are produced with CNC machining. Manufacturing with machining means starting from a block of metal and removing the material that is not necessary, leading to a high buy-to-fly ratio which is the ratio of the weight of raw material purchased to the weight of the final part. The buy-to-fly ratio for machined parts ranges up to 12:1, meaning that 12 kilograms of metal are used to manufacture 1 kilogram of product, while additive manufacturing can reach values close to 1:1.

3.5.5 Obsolescence Problems Mitigation and Management

As anticipated in the first chapter, Additive Manufacturing shows great potential in mitigating obsolescence problems. Obsolescence is the condizione di quegli articoli di fornitura che, comunque richiesti e/o necessary durante il ciclo di vita in esercizio del prodotto, non sono più acquistabili, supportabili, o riparaili da parte della ditta o di un suo fornitore, per una serie di possibili cause quali:

- Innovazione tecnologica, che comporta l'introduzione sul mercato di nuovi component e conseguente abbandono/superamento di quelli precedentemente impegati.
- Evoluzione della strategia di business dei produttori di una tecnologia (e.g. semiconduttori) per ragioni di mercato (e.g. performance e consumi) che non sono guidate dale esigenze dei settori Aerospazio e Difesa, che può indurli ad abbandonare tali settori per dedicarsi ad altri più redditizi e con requisiti di performance e affidabilità meno stringenti (e.g. quello della componentistica electronica per l'informatica e il più largo mercato "consumer".

- Evoluzione o interruzione delle fonti di approvigionamento (e.g. cessata attività di un fornitore, perdita o mancato rinnovo di licenze, embarghi, materiali dichiarati proibiti o pericolosi dalle normative o dalla legge).
- Evoluzione delle normative: aggiornamento, evoluzione, migrazione delle Specifiche Tecniche e Standard.
- Termine della produzione (e.g. smantellamento della linea di produzione, oppure superamento del processo e/o dei tool di lavorazione, divenuti essi stessi obsolete).
- Impossibilità di testare equipaggiamenti e/o GSE per avvenuta obsolescenza del test equipment.
- Perdita di know-how, di documentazione di Progetto e/o produzione

L'obsolescenza tecnologica è un fenomeno che insorge nel momento in cui il Sistema primario ha un ciclo di vita notevolmente più lungo dei suoi component, per cui è inevitabile per I prodotti del settore Aerospazio e Difesa I cui prodotti hanno una vita in esercizio che in alcuni casi si estende oltre I 30 anni.

Per ciascun Sistema, equipaggiamento, assieme, componente, e materiale del prodotto, viene eseguita una analisi del rischio di obsolescenza (ORA – Obsolescence Risk Assessment) su base reattiva o proattiva che consiste in una valutazione di costo-probabilità del rischio di obsolescenza. Per quanto citato, è divenuto essenziale sviluppare un Piano di Gestione delle Obsolescenze (OMP – Obsolescence Management Plan) che definisca le strategie da mettere in atto per l'identificazione e la mitigazione degli effetti dell'obsolescenza. Ciò richiede di individuare, analizzare, ricercare e definire soluzioni il più possibile preventive all'insorgenza di degrade della supply chain, del support logistico, del life cycle cost, dell'operabilità del prodotto in servizio, e della customer satisfaction.

L'obsolescenza è inevitabile ma può essere gestita e I suoi effetti mitigate, con costi delle azioni correttive che crescono man mano che il componente di interesse raggiunge uno stato di decline che lo conduce verso una condizione di osbsolescenza conclamata. È perciò necessario mantenere un monitoraggio proattivo dell'obsolescenza e attuare una ricerca e valutazione preventiva di soluzioni e/o fornitori alternativi.

Una analisi tecnica ed economica permette di valutare le possibili soluzioni, tra le quali:

- Effettuazione di un Last Buy Order a copertura dell'esigenza di support per l'intero orizzonte logistico del prodotto o per il tempo necessario al suo aggiornamento.
- Sostituzione del particolare con un equivalente/alternativo.
- Parziale o complete re-design dell'apparato ed eventuale riqualifica.

- Sostituzione integrale dell’apparati con altro immediatamente disponibile, che garantisca prestazioni uguali o superiori.

Queste soluzioni richiedono effort notevoli da parte dell’azienda e sono fonti di rischio: l’effettuazione di un Last Buy Order da un fornitore non è sempre fattivile o potrebbe portare a lead time di approvigionamento inaccettabili, mentre un redesign o la sostituzione del componente potrebbero essere soluzioni sottoposte a vincoli tecnologici/logistici con conseguenze nel lungo termine, che quindi devono essere valutate a 360 gradi.

L'adozione dell’additive manufacturing all’interno dell’azienda permetterebbe di sfruttare le potenzialità e la flessibilità di questa tecnologia per mitigare problemi di obsolescenza che richiedono ad oggi molto effort da parte della compagnia e possono portare a soluzioni anti economiche o al pagamento di penali. Due fattori in particolari rendono interessante la valutazione della tecnologia come soluzione a lungo termine o temporanea per l’obsolescenza dei component:

- Leonardo’s small volumes of production and the reliance on previous platorms for design, that fits the “should-have” characteristics of the ideal AM candidate
- AM manufacturing systems’ capabilities of produce a large variety of geometries ad types of components

With Additive Manufacturing integrated as a manufacturing technology for spare parts, the company has the opportunity to fulfill for the esigenza for the remaining life cycle of the product or cover until an alternative supplier is found or a long-term solution is developed, such as a last-time provisioning or a redesign of the component is completed.

CHAPTER 4: OVERVIEW OF AM IN THE AEROSPACE INDUSTRY

4.1 Introduction

Additive manufacturing (AM) is increasingly recognized as a pivotal technology in the aerospace industry, with significant implications for both civil and military applications. As of today, the aerospace sector holds the largest share of interest in AM, particularly in the areas of rapid prototyping and the production of final, functional parts. The growing adoption of AM can be attributed to its ability to produce highly complex, lightweight, and customized components, which are critical for aerospace applications. Companies such as Boeing and Bell Helicopter were among the pioneers in integrating AM into their manufacturing processes, with Boeing currently utilizing over 70,000 additive-manufactured parts on both its civil and military aircraft. This not only highlights the technological maturity of AM but also underscores its role in meeting the stringent quality and performance standards required in the aerospace sector.

The use of AM extends beyond prototyping to the production of final components, particularly those requiring intricate geometries that would be difficult or impossible to manufacture using traditional methods. For example, AM is now being employed in the production of complex propulsion components, where both material properties and shape intricacy are crucial. Companies such as MTU Aero Engines in Germany and Turbomeca in France have adopted AM to produce high-performance parts, such as fuel injector nozzles and combustion swirlers, which must withstand extreme operating conditions. The flexibility of AM allows for on-demand production, reducing inventory costs and lead times, which is particularly advantageous in the aerospace supply chain, where maintenance and spare part availability are critical to operational readiness.

4.2 Technologies for Aerospace

While AM offers many advantages, there are still significant challenges, particularly in the selection of suitable materials. For instance, certain aluminum alloys commonly used in aerospace, such as the 2XXX series (copper-based) and 7XXX series (zinc-based), present issues when used in AM due to their susceptibility to solidification cracking. These alloys are not considered weldable, which limits their compatibility with fusion-based AM processes. This material limitation poses a challenge when evaluating the feasibility of producing specific spare parts through AM.

The Additive Manufacturing procedures that meet aerospace requirements, according to the Wholers Association, and the categories which they belong to are reported in the table.

Procedure	Process Category
Selective Laser Sintering (SLS)	PBF
Selective Laser Melting (SLM)	PBF
Electron Beam Melting (EBM)	PBF
Wire and Arc Additive Manufacturing (WAAM)	DED
Fused Deposition Melting (FDM)	MEX

The following table matches procedures with materials available

	PBF	DED	BJT	MEX	MJF
Thermoplastic polymers	X		X	X	
Thermoset polymers					X
Elastomer polymers	X			X	X
Composites	X		X	X	X
Metals	X	X	X	X	X
Hybrid Metals	X	X		X	
Ceramics	X		X	X	X

Despite the constraints, the use of AM in the aerospace sector, especially in the military domain, is expanding rapidly. The technology not only allows for greater design freedom and the creation of lighter, stronger parts but also plays a key role in enhancing supply chain resilience. In military aerospace, where the timely availability of spare parts is crucial for maintaining aircraft readiness, AM enables decentralized manufacturing, potentially allowing parts to be produced directly at maintenance depots or even in-theater. This capability reduces logistical bottlenecks, shortens lead times, and enhances operational flexibility, providing a strategic advantage in military operations.

4.2 Military certification standards

In the field of aviation, certification is a critical and highly stringent process, particularly in civil aviation, where regulations are enforced by international organizations like the International Civil Aviation Organization (ICAO). These regulations ensure safety, airworthiness, and compliance across all nations involved in civil aviation. In contrast, the military aviation sector lacks a unified certification standard across the European Union (EU). Each EU member state has historically developed its own set of airworthiness regulations, resulting in a fragmented approach to the certification of military aircraft. This decentralization creates challenges for cross-border collaborations and complicates the process of ensuring uniform safety and operational standards across military fleets.

Recognizing the inefficiencies and potential barriers to collaboration posed by these discrepancies, efforts have been made to unify military airworthiness standards. One of the most notable developments in this area came in 2008, when the European Defense Agency (EDA) initiated the creation of the Military Airworthiness Authorities (MAWA). This initiative brought together representatives from 27 EU countries to form a joint assembly tasked with harmonizing military airworthiness standards. Over time, this collaboration has yielded significant progress, most notably the development of the European Military Airworthiness Requirements (EMAR). These standards are designed to streamline and unify the processes involved in certifying and maintaining military aircraft, with the goal of fostering greater cooperation between EU member states and easing the complexity of cross-border military operations.

In the context of this thesis, which focuses on the integration of additive manufacturing (AM) in the supply chain for military aeronautical spare parts, the primary concern is ensuring continuous airworthiness. As AM is increasingly applied to the production of spare parts, the importance of adhering to certification standards becomes paramount. Two specific EMAR regulations are especially relevant: EMAR M, which deals with continuing airworthiness, and EMAR 21, which governs the certification of aeronautical products and parts. These regulations set the framework for ensuring that AM-produced components meet the rigorous safety and performance standards required for military aircraft. In Italy, compliance with these standards is overseen by the "Direzione degli Armamenti Aeronautici e per l'Aeronavigabilità" (DAAA), the national authority responsible for military airworthiness.

However, the application of AM in producing military spare parts presents unique challenges when it comes to meeting certification standards. While AM technology has advanced significantly, particularly in its ability to produce high-quality parts, there remain issues with process repeatability and reliability, which are critical factors in airworthiness certification. The consistency and quality of AM processes must be ensured to produce components that can be reliably used in aircraft, where failure is not an option. These challenges are closely tied to the maturity of the technology itself, which is often evaluated using the Technology Readiness Level (TRL) scale. This scale, which ranges from basic research at TRL 1 to proven operational systems at TRL 9, is used both in Europe and the United States to assess the development stage of new technologies. Currently, AM for military spare parts has not yet reached the desired TRL for widespread adoption, largely due to the complexity of ensuring that each part produced through AM meets the rigorous standards required for military applications.

One of the major hurdles in advancing AM technology for military spare parts is the lack of clear, comprehensive regulations specific to additive manufacturing. Without standardized guidelines governing the use of AM, it is difficult for manufacturers to consistently produce parts that meet certification requirements. However, the international community is making strides in addressing this gap. Recognizing the potential of 3D printing and its applications in industries like aerospace, international standard-setting bodies such as the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have joined forces to create standards for AM. These standards are being developed in three main categories: general standards, standards for material categories, and standards for specific materials, processes, or applications. By mid-2023, ASTM International had already published 33 standards related to the AM industry, covering fundamental aspects such as terminology, design requirements, and testing methodologies.

In addition to these efforts, other major organizations are also contributing to the establishment of AM standards. For instance, NASA has released technical standards specifically for spaceflight hardware manufactured through laser powder bed fusion, a common AM process. NASA's standards, such as MSFC-STD-3716, provide detailed guidelines on material characteristics, structural demand criteria, part production plans, and post-processing treatments. These guidelines are essential for ensuring the reliability and safety of additively manufactured parts, particularly in critical aerospace applications.

Despite these advances, there is still a gap between the current ISO standards, which focus primarily on final material properties and defects, and the more comprehensive process specifications needed for aerospace applications. This is why organizations like SAE International's Aerospace Material Specifications (AMS) committee are working to develop process standards specifically for both metallic and polymer-based additive manufacturing materials and safety-critical components. These efforts reflect the growing recognition among regulatory bodies that AM is poised to play a transformative role in aerospace manufacturing, including in the military sector.

In summary, while the certification of AM-produced military spare parts remains a complex issue, significant progress is being made toward establishing the necessary standards and regulations. The ongoing work by organizations such as ISO, ASTM, and NASA, along with the unified efforts of the European Defense Agency through MAWA, signal that additive manufacturing is expected to evolve rapidly in the coming years. As certification frameworks continue to develop, the integration of AM in military aviation is likely to expand, offering enhanced flexibility, cost efficiency, and innovation in the production of critical components.

4.3 Additive Manufacturing for Production and MRO

Maintenance, Repair, and Overhaul (MRO) operations are significantly influenced by logistical strategies and support systems. Ensuring the availability of spare parts, both at the main base and in operational theatres, plays a crucial role in enhancing fleet readiness. The availability and readiness of spare parts are key factors in addressing Aircraft Out of Commission for Parts (AOCP) situations. Minimizing downtime not only reduces associated operational costs but also ensures the continuous availability of aircraft, which is essential for maintaining mission readiness and operational efficiency.

To date, logistic support in Leonardo is organized around a series of dedicated warehouses, which represent the pool of available spare parts. In those pools, parts are ready for delivery when requested by customers. This requires pool management through strategies and algorithms that allow Risk of shortage analysis and the consequent restocking to ensure availability.

The AM4Logistics project is designed to be classified as a lean management strategy. Lean management refers to a strategic approach characterized by the close integration of personnel with production processes, and a shift in development and production control that emphasizes market-driven demand. One of the primary objectives of lean management is to increase the proportion of Just-In-Time (JIT) deliveries. In its strictest sense, JIT refers to producing only what is needed by the customer, exactly when it is needed. The application of JIT aims to reduce, and ideally eliminate, all forms of waste within the production environment and in supply chain relationships. From a logistic point of view, adopting AM in the supply chain for spare parts would bring enormous benefits:

- Weight and waste reduction
- Reduced warehousing and inventory management effort

- Reduced transportation
- Shorten critical turnaround time for spare parts supply
- Mitigated risks of AOG events

Integrating additive manufacturing in the production of spare parts would mean cutting off the steps, shortening the chain and thus speeding it up. Furthermore, having a smaller supply chain implies decreasing failure risk, since there are less critical point and less operators.

Additionally, AM allows to improve Customer Support's service by allowing a ready solution for obsolescence management. As anticipated in paragraph 1.1, obsolescence is defined as the condition of supply items that, although required and/or necessary during the operational life cycle of the product, are no longer purchasable, supportable, or repairable by the company or its supplier. Obsolescence is inevitable but can be managed, and its effects mitigated; the costs of mitigation actions increase as the component/material reaches a state of decline that leads to a condition of full obsolescence. AM offers opportunities to mitigate these situations as is explained in paragraph 4.4.

Decentralized systems allow for a faster response to client demand. Due to the degree of unpredictability of demand for spare parts, characteristic of this shipment system is a key advantage. On the other hand, a centralized production is nowadays definitely more cost effective than decentralized one. In view of the development of new technologies and the increase in the degree of automation, decentralized production is not excluded.

Thus, from a logistics perspective, there are three possibilities for parts production:

- Leonardo itself produces parts according to the customer's request: it provides the highest flexibility and greatest control for the OEM. It is directly suitable for 'make' parts (the ones produced by OEM, as opposed to 'buy' parts) and the process can be fully structured and qualified with company regulations.
- Leonardo establishes a network of certified suppliers to produce parts.
- The client is directly responsible for production.

These models have different opportunities and threats that are exposed in the next chapter.

Furthermore, AM's unique capability to create complex and customized components directly from digital models allows for more flexible and efficient manufacturing processes. While anything is theoretically producible, leverage on freedom of design offered by AM is most appropriate to reduce material waste (buy-to-fly ratio) and effectively lower weight and improve performance (topology optimization). For this reason, candidate parts are preferably characterized by rather complex and intricate geometries while having contained dimensions.

To better take advantage of AM's complexity for free and make use of topological optimization for better performance, optimizable designs (for example including lattice structures for weight savings) are highly desirable.

Concerning materials, the technologies allow for production of parts in polymers and metals. For polymers, Fused Deposition Modelling (FDM), Stereolitography (SLA) and Selective Laser Sintering (SLS) are robust technologies. Investment costs are relatively low, the materials catalogue is varied, and as-built parts exhibit attractive properties.

For metals on the other hand, powder-based technologies are usually preferred. Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) are well established solutions, showing great potential although not exactly cheap due to high investment costs.

While the production of fiber composites remains challenging, a lot of research is being carried out for several years and results are promising.

4.4 Global market for spare parts in Additive Manufacturing

Leonardo Aircraft has been at the forefront of Additive Manufacturing with more than hundreds of parts, both in metal and in polymer, qualified and flying on all platforms. The company is exploring the convenience of integrating AM technologies for Logistic Support activities. Major competitors have also shown interest in investing in research and development for military AM application. Such a marked interest is linked to the element that would most benefit from the use of 3D printing for maintenance purposes: lead time. In the field of Defense and Security, assets availability is one of the most critical requisites. Additive Manufacturing, allowing for flexible production "Just in Time", enables a potential level of readiness and availability unmatched. NATO has put a lot of resources into research and experimentation around this technology and the following two documents are particularly relevant due to the issues they address.

The first one is titled "Additive Manufacturing –Rapid Support System (AM-RS2): Concept Design of a deployable AM unit for War Theatre" [A. Busachi et alii, "Additive Manufacturing –Rapid Support System (AM-RS2): Concept Design of a deployable AM unit for War Theatre", STO-MP-AVT-267]. The project aims to develop a deployable Additive Manufacturing unit to support soldiers stationed in remote Areas of Operation. It was presented to the United Kingdom Ministry of Defense

(MoD), which recognized the significance of the study, particularly in its potential real-world applications.

The research focuses on two key innovations. The first is the introduction of portable 3D printing machines, named the Additive Manufacturing Rapid Support System (AM RS2). Each AM RS2 unit is a turnkey, fully integrated, and automated system that utilizes Fused Deposition Modelling (FDM) technology. These user-friendly machines are equipped with everything necessary to produce a component, including a CAD computer, a 3D printer, and a 3D scanner. However, given the nature of FDM technology, the primary limitation lies in the restricted range of materials, as the system primarily supports plastic-based components.

The second major aspect of the research is the innovative use of the 3D scanner, which is based on the principles of reverse engineering. This process involves capturing the geometry of an existing component to generate a CAD file, thereby allowing the reproduction of the part without relying on original technical drawings.

The document outlines various potential applications, such as manufacturing spare parts or prosthetic devices. However, while the concept offers promising possibilities, the research has yet to fully demonstrate a proof of concept for these applications.

The second relevant document is entitled "Modelling Applications of Additive Manufacturing in Defense Support Services: Introducing the AM -Decision Support System" [Modelling Applications of Additive Manufacturing in Defense Support Services: Introducing the AM -Decision Support System, STO-MP-AVT-267-03B]. The research explores the logistics of additive manufacturing and conducts a cost-benefit analysis. It compares traditional military logistics with those incorporating 3D printing technology. Specifically, the study references a division of the US Army, established in 2010, known as the "Rapid Equipping Force" (REF). The REF is tasked with delivering timely solutions for battlefield scenarios. The US Department of Defense (DoD) has invested a substantial $2.8 million into this initiative, reflecting its strong commitment to advancing additive manufacturing within military operations.

Given that the REF's primary focus is on researching and applying additive manufacturing technologies, the significant interest from the United States serves as a catalyst for similar research efforts in other countries. Although the paper introduces a mathematical model to support cost and feasibility analyses for the adoption of additive manufacturing, this model has not yet been implemented.

Despite extensive research, no publicly available evidence has been identified that demonstrates the successful implementation of Additive Manufacturing technologies for the production of critical spare parts. Nevertheless, it is highly probable that numerous successful cases exist, particularly within the Defense and Aerospace sectors, where technological readiness is advanced among key stakeholders, including Leonardo.

One of the few openly disclosed collaborations concerning the application of AM for spare parts production is a partnership involving France, Germany, and Belgium. This initiative includes three prominent companies—Deutsche Aircraft, Airbus, and Materialise—working jointly to explore the potential of AM in this context. Materialise is a company specializing in additive manufacturing and is certified for the production of aerospace spare parts. It is reported that they have produced over 26,000 in-flight components for Airbus. The parts in question, depicted in Figures 19 and 20, are non-critical components that do not endure significant structural stress.

The first part, shown on the left, is a storage compartment panel, made 15% lighter through optimized use of additive manufacturing technology. The second part, on the right, is a flight-ready snap-fit polymer component for the Deutsche 328 aircraft (courtesy of Materialise, as cited in the Wohlers Report 2022).

Figure 19: Compartment panel

Figure 20: Snap-fit polymer part

In conclusion, while significant advancements have been made in the application of AM technologies within the aerospace and defense sectors, the full potential of these innovations, particularly in the production of critical spare parts, remains largely unexplored in public literature. The current use of AM for non-critical components, such as those produced by Materialise for Airbus and Deutsche Aircraft, demonstrates the feasibility of manufacturing complex parts with reduced weight and optimized materials. However, given the logistical advantages and cost-efficiency that could be realized, further research is recommended to explore the implementation of AM for in-situ production of plastic spare parts. Such a study could assess the viability of deploying AM systems directly in operational environments, potentially revolutionizing supply chains by enabling rapid, on-demand production of essential components in remote or high-pressure scenarios.

CHAPTER 5: AM IN LEOARDO AIRCRAFT

5.1 Introduction

Additive manufacturing is gaining significant traction in the aerospace industry due to its ability to enhance logistic efficiency, reduce efforts, and support complex design solutions that characterize the industry. In particular, leveraging AM for the production of spare parts has the potential to disrupt how companies such as Leonardo manage their supply chains and support fleets.

In this chapter, after an introduction on the utilization of the technology within Leonardo Aircraft as of today, the future opportunities for the technology are exposed. The three business models considered by Leonardo for integrating additive manufacturing into the spare parts supply chain are then introduced. AM offers the capability to produce parts on demand with significantly reduced lead times, avoiding the complexities of traditional supply chains. When urgent spare parts are needed, AM can be conducted in-house or close to the point of use, eliminating long shipping durations and reducing warehousing and transportation costs. The technology shows therefore the potential to disrupt the supply chain at some level.

5.2 Additive Manufacturing in Leonardo today

Leonardo Aircraft has been working with Additive Manufacturing for several years and has introduced the technology in production since 2015, with hundreds of parts produced and flying. For the M-345, the M-346 and the C-27J aircrafts more than 100 parts are qualified. These parts are produced using Power Bed Fusion (PBF) systems in AlSi10Mg for metal parts and Fused Deposition Modeling (FDM) in Ultem9085®. It is worth noting, for example, the collaboration between BEAMIT® Group and Leonardo Aircraft for supplying a number of additively manufactured components over the coming years.

5.2 Strengths and Limitations for practical applications

Additive manufacturing offers significant advantages in the production of spare parts for the industry, which can be strategically leveraged to optimize operational efficiency. One of the primary benefits is the reduction in lead time for sourcing, as components can be manufactured quickly and locally, minimizing delays in part availability. This capability also mitigates the risks of stock depletion and obsolescence, both critical factors in maintaining the readiness of fleets. The flexibility of on-demand production eliminates the need for large inventories, thereby reducing the capital tied up in surplus stock. Additionally, in-situ production capabilities enable the manufacture of parts directly at the point of use, further enhancing logistical efficiency.

However, despite the disruptive capabilities, there are characteristics of both the technology and the industry framework that limit the cases in which Additive Manufacturing's features can be leveraged. The technical limitations are directly tied to the manufacturing system available, and are related to mainly four matters, regardless of the specific AM process:

- **Dimensions**: does the part fit in the building chamber?
- **Material**: Does an appropriate material for the component exist in AM?
- **Geometry**: are the geometries feasible with a 3D printing system? (Critical geometries: cavities, canals, thin walls, etc.)
- **Quality:** Does the finished product meet the technical and quality requirements?

For the interests of Leonardo Aircraft, the constraints tied to these matters are relevant but not definitive. Materials suitable for aerospace applications are available such as titanium and AlSi10 (some are exposed in chapter 3) and the dimensions of the build chambers of well-established AM producers are suit for a wide range of parts of interests. Geometry constraints limit this range, nevertheless a process of redesign could be feasible if necessary.

In addition to technical evaluation, the use of additive manufacturing technologies requires a comprehensive cost-effectiveness assessment. This evaluation must compare the costs of components produced through additive manufacturing with those produced using traditional methods. Such an assessment should encompass all economic factors related to the production of components using both technologies.

It is insufficient to consider only operational costs, which are directly linked to the manufacturing, assembly, and management processes (e.g., transportation, inventory, and logistics). Equally, if not more in some cases, important are the costs associated with meeting qualification and quality standards, which can be substantial and may determine the economic viability of the technology. The qualification of new processes, materials, and equipment is often time-consuming, complex, and costly. To date, as mentioned in paragraph 3.2, Leonardo has qualified three materials for production: Ti-6Al-4V and AlSi10Mg for PFB and ULTEM9085 for FDM with the publications NTAs. As of today, more than 100 parts are qualified and operates on several platforms, from trainers as the M-345 and M-346 to airlifters such as the C-27 J and ATR. [BEAMIT and Leonardo sign 3D printing series production agreement (metal-am.com)]

A key to success with AM is comprehensive and realistic cost justification: when a simple one-to-one cost comparison between AM and conventional processes is made, the range of products for which AM is suited is small. Instead, the broader product life cycle should be considered, alongside the total manufacturing costs.

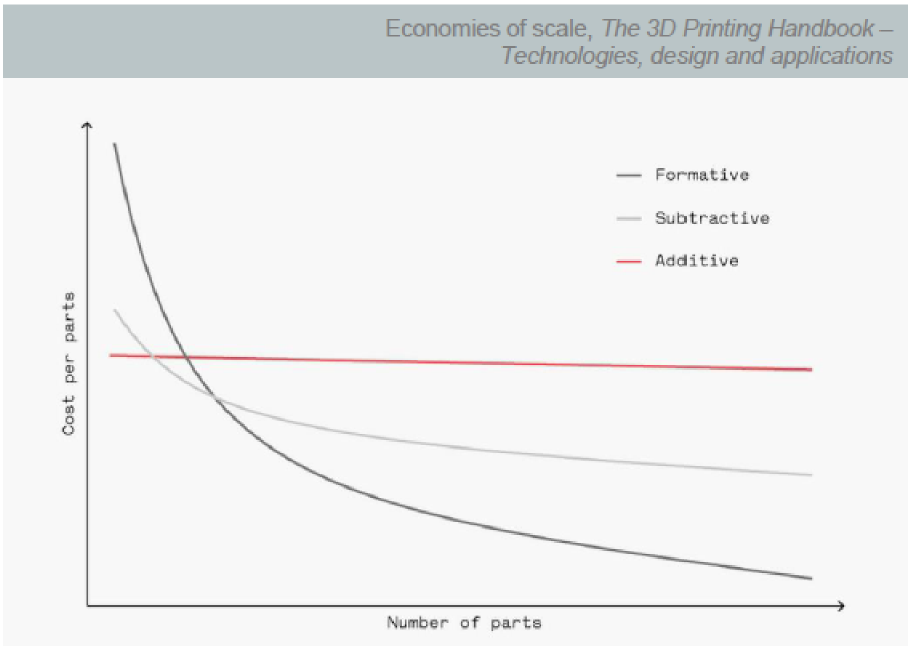
Additive manufacturing may be justified when a spare part needs to be put into service quickly. In the event of an Aircraft on Ground (AOG) situation, the downtime of the aircraft results in significant costs and could also lead to penalties. A similar issue arises when delays occur in delivering parts to clients due to reliance on external suppliers: the more a part is transported between locations for manufacturing and finishing, the greater the risk of disruptions. One the main benefit of AM is the ability to produce virtually any geometry so a network of AM producers would be more resilient to disruption, which could prevent damages due to failure of suppliers or costly operations of obsolescence management.

The convenience of integrating additive manufacturing should be evaluated considering also the longer-term opportunities that the technology enables. Existing spare parts designs can be subject to a redesign process to leverage the potential of Additive Manufacturing during the life cycle of the aircraft. One of its key advantages is the ability to create complex geometries that would be difficult or impossible to achieve using traditional manufacturing methods. This capability allows engineers to design parts that are not constrained by the limitations of conventional processes, thus improving performance and reducing material waste. Additionally, AM enables assembly consolidation by reducing the number of individual components required for a given system. This not only simplifies manufacturing and the management of documentation, but also enhances reliability by minimizing potential failure points. Furthermore, AM allows for the customization of parts, making it possible to produce spare components tailored to specific requirements, which is especially beneficial in the aerospace sector where unique designs and low production volumes are often needed. Together, these factors position additive manufacturing as a disruptive technology for producing aerospace spare parts efficiently and cost-effectively.

5.3 Operating Costs Items for AM production

In order to evaluate the convenience of manufacturing a component in AM or traditional technologies, it is important compare direct and indirect costs considering the whole life cycle of the part. In the next paragraphs the cost structure for Power Bed Fusion systems and Filament Deposition Modeling systems are introduced. These two technologies were chosen given their relevance for the aerospace industry. Considering the lack of practical data on one hand, and on the other the cost confidentiality of strategical cost-related data, an accurate cost analysis is not provided. Some publicly available data are to be provided as an example.

One aspect of the cost structures that is valid and relevant for virtually all AM processes is the absence of manufacturing tooling. In comparison, both subtractive manufacturing and casting requires specific tools to keep the part in place during chip removal or the molds for casting. The design, production, and handling of these tools are costly processes that affect the lead time of the parts. The absence of non-recurring costs (NRC) reduces the effort for designing and production.



5.3.1 Power Bed Fusion Cost Breakdown

Powder Bed Fusion is an additive manufacturing process where a laser or electron beam selectively melts a metal powder to form components layer by layer. The cost elements associated with the production process include:

- **Printing File Preparation**: This process can become time-intensive if the part requires redesign, not considering additional consideration for Design Review certifications, but generally, preparing the job for printing requires a comparable effort to traditional manufacturing techniques (Gibson et al., 2021).
- **Metal Powder Cost**: The pricing of metal powders used in PBF is typically unpublished, but for industrial applications, it can range from $20 to over $250 per kg (Wohlers, 2020). Factors affecting cost include material precursors, particle size, order quantities, and socio-economic conditions (Herzog et al., 2016). Given the stringent requirements of the aerospace sector, the price tends to be on the higher end of this range. Inefficiencies in material usage impact raw material costs: while the buy-to-fly ratio can approach 1:1, a portion of the powder is lost in supports, sintered layers near the part, and filtration systems (Frazier, 2014). At last, unprocessed powders can not be recycled indefinitely and usually three to five times is considered the limit.
- **Machine Usage Cost**: The hourly cost of machine operation includes energy consumption, process gases, consumables like lenses and air filters, labor (since systems often require the supervision of skilled operators), and equipment depreciation. High-end metal AM machines can cost up to $2 million, with depreciation extended over several years (Wohlers, 2020). In addition to the core machine, ancillary equipment such as special powder storage, sieving systems, explosion-proof vacuums, and gas sensors must be factored into the amortization costs. Machine setup and teardown are time-consuming processes, further increasing cost per job (Herzog et al., 2016).
- **Heat Treatment Cost**: All metal parts produced via PBF require post-build heat treatment to alleviate residual stresses. The cost is influenced by oven size, part dimensions, and local energy costs (Gibson et al., 2021).
- **Removal from Build Platform**: Costs for removing parts from the build platform vary depending on the part's geometry, dimensions, and material, as well as the equipment required (Frazier, 2014).
- **Support Removal Cost**: This cost depends on the amount and type of support structures used, as well as the operator's hourly rate (Gibson et al., 2021).

- **Surface Finishing**: Surface finishing is critical in aerospace due to stringent qualification requirements. If surface finishing requires advanced CNC machining, it can become a production bottleneck, negating the lead time benefits of AM (Herzog et al., 2016).
- **Dimensional Control**: The cost of dimensional inspection correlates with part size and complexity, with more intricate parts requiring more time on high-precision equipment (Gibson et al., 2021).
- **Destructive and Non-Destructive Testing**: Since AM falls under Leonardo's special process guidelines, every AM-manufactured part must undergo stringent testing, including radiography, tomography, and destructive testing, to verify mechanical properties (Wohlers, 2020).

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5.3.2 Fused Filament Fabrication Cost Breakdown

Fused Filament Fabrication is an additive manufacturing process that builds polymer parts by extruding thermoplastic filament through a heated nozzle in successive layers. The cost items of the process are as follows:

- **Printing File Preparation**: The effort required to prepare files for FFF is typically lower than for metal-based processes like PBF. While some complex geometries may require redesign, file preparation is generally straightforward and comparable to traditional plastic fabrication methods (Gibson et al., 2021). As explained in following chapters, this item would be Leonardo's responsibility.

- **Filament Cost**: FFF utilizes spools of thermoplastic filament, which is significantly less expensive than metal powders used in PBF. Filament costs range from \$20 to \$100 per kg, depending on the material (Wohlers, 2020). Aerospace-grade polymers like PEEK or PEI (ULTEM) tend to be at the higher end of this range (Compton & Lewis, 2014). Filament usage is more efficient compared to powder-based methods, as there is little material waste outside of support structures (Peng et al., 2021).

- **Machine Usage Cost**: The operational cost of FFF machines is generally lower than for PBF due to lower energy requirements, reduced need for consumables, and less labor-intensive supervision. FFF machines range in price from a few thousand to several hundred thousand dollars for industrial models, and they do not require complex ancillary equipment (Peng et al., 2021). Depreciation costs for FFF equipment are thus lower than those for metal AM processes. However, setup and teardown times, while shorter than PBF, still contribute to overall machine occupancy and costs (Compton & Lewis, 2014).

- **Post-Processing**: FFF parts may require post-processing, particularly support removal and surface smoothing. Support removal is simpler compared to PBF and can often be automated or done manually at a lower cost. Surface finishing may involve techniques like sanding, chemical smoothing, or coating, but these are generally less resource-intensive than the surface treatments required for metal parts (Peng et al., 2021).

- **Dimensional Accuracy and Control**: FFF systems have lower inherent accuracy compared to PBF, especially when working with high-performance polymers. However, the cost of dimensional checks remains significant for aerospace applications, as critical dimensions need to be verified, though this is generally less costly than for metal parts (Gibson et al., 2021).

- **Testing and Qualification**: Like other AM processes, FFF parts for aerospace must meet stringent qualification standards. While destructive and non-destructive testing is required, the costs are typically lower than those for metal AM parts due to the less critical mechanical properties of polymers. Testing may include visual inspection, radiography, and tensile testing of samples (Peng et al., 2021).

References:

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5.3 The Business Models

In the context of integrating Additive Manufacturing within the supply chain, Leonardo Aircraft is considering several ways to take advantage of the technology and streamline production. In the following paragraphs, the three considered models are introduced.

5.3.1 Support

In the first business model, Leonardo offers a solution where the customer takes full responsibility for the production of parts using additive manufacturing (AM) technology. This model envisions AM equipment being available directly at customer bases or even as mobile solutions, potentially installed on the aircraft itself. The customer oversees the production, which is supported by detailed part models and operational guidelines provided by Leonardo. To ensure success, Leonardo also offers comprehensive training and remote support, enabling customers to independently produce parts. This approach is particularly suited for simpler, non-critical components, such as FDM-manufactured plastic parts like buttons, knobs, supports, and other consumables. By decentralizing part production to the customer, this model allows for faster, on-demand manufacturing of lower-risk components, while still ensuring that the customer operates within a framework designed and supported by Leonardo.

5.3.2 Leonardo Hubs

The second model sees Leonardo establishing its own network of proprietary AM hubs, strategically positioned to serve key regions. These hubs would be fully owned and operated by Leonardo, equipped with a range of advanced AM technologies capable of producing more complex parts, including metallic components that require rigorous certification. The hubs would be staffed by a multidisciplinary team of experts, including designers, mechanical engineers, materials scientists, and logistics and quality control personnel, ensuring that each part produced meets the stringent requirements of the aerospace industry. This model is ideal for the production of high-value, critical components where quality and certification are paramount. By centralizing production within Leonardo-owned hubs, this approach ensures tighter control over the manufacturing process, while positioning the company as a leader in advanced aerospace AM applications.

5.3.3 Suppliers Network

The third business model leverages a growing global network of AM service providers to guarantee part delivery for Leonardo. In this scenario, Leonardo establishes partnerships with qualified suppliers who own and operate the necessary AM resources. These suppliers are strategically selected based on their capabilities and geographical location, which allows for optimization of logistics and reduction of lead times. By tapping into the existing ecosystem of AM service providers, this model offers flexibility and scalability, enabling Leonardo to meet varying demands without the need for significant in-house AM capacity. The distributed nature of the supplier network ensures that production can be localized conveniently, reducing transportation costs and increasing responsiveness, while still adhering to Leonardo's strict quality standards for parts.

5.4 Scale-up challenges

CHAPTER 6: THE SUPPORT MODEL FOR POLYMER PARTS

6.1 The Vision behind the Support Model – AM as a Service (AMaaS)

In line with the growing demand for agility and efficiency within the aerospace and defense sector, Leonardo Spa is exploring a forward-thinking business model that harnesses the full potential of additive manufacturing. Following global trends, the company's vision centers around a support model that empowers customers, shifting the traditional spare parts supply chain paradigm by decentralizing production and bringing manufacturing capabilities directly to the customer's operational base. Rather than relying on centralized production facilities and extended lead times, Leonardo envisions servicing its client with additive manufacturing systems, along with all the necessary equipment and knowledge, particularly for non-critical components such as FFF-manufactured plastic parts. This shift allows for localized, just-in-time production that dramatically reduces turnaround times and enhances operational flexibility.

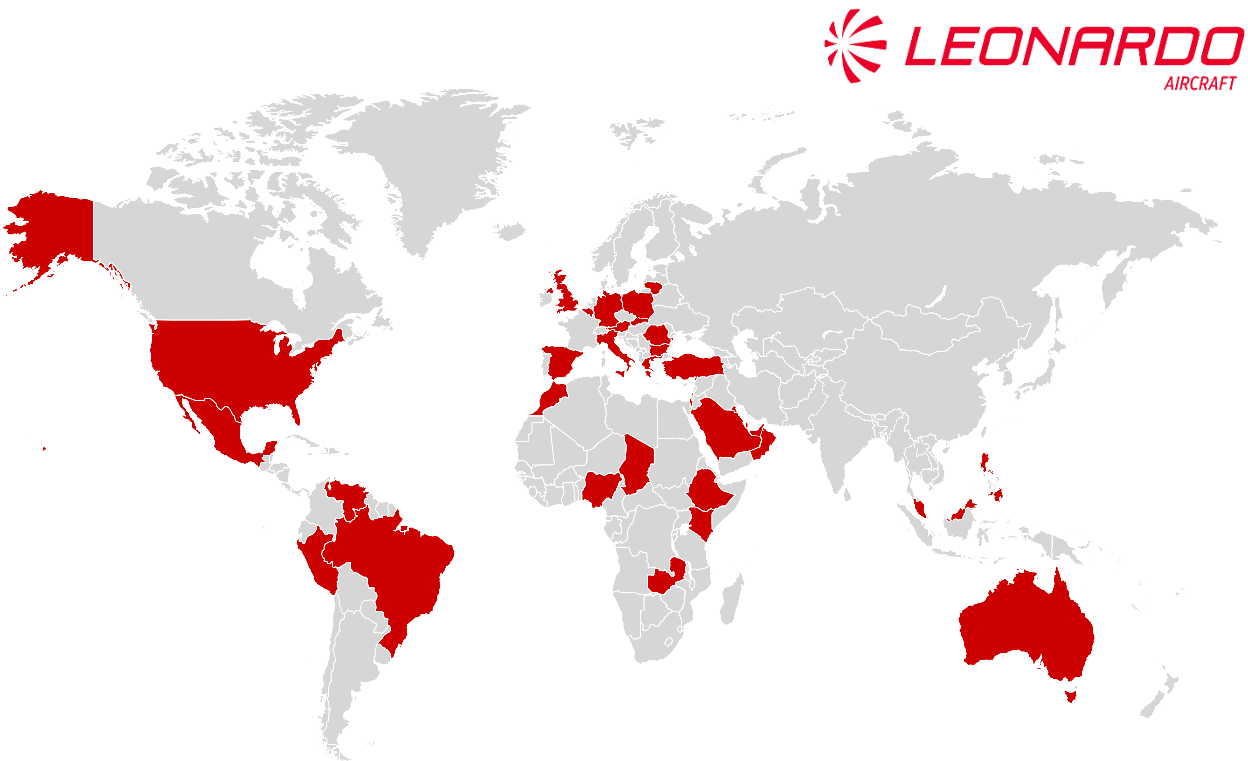
The core of this model is the service-like nature and seamless support provided by Leonardo. Customers receive not only all the necessary equipment for manufacturing but also a catalogue of detailed part models and comprehensive operational guidelines for all the manufacturing procedures, from pre-processing to post-processing. This ensures that production is carried out efficiently and in line with the industry's high standards. To further enable customer independence, the company offers thorough training programs and continuous remote support, enabling customer collaboration for updating the catalogue every year, based on needs that the specific clients discover during their operations. The combination of hands-on training and responsive assistance allows customers to confidently oversee the production process, minimizing downtime and ensuring operational efficiency.

Leonardo's vision is particularly well-suited to the production of simpler, non-critical components, such as FFF-manufactured plastic parts like buttons, knobs, supports, and other consumables. Potential candidates are also Ground Support Equipment (GSE) components or assembly tools, parts which, if missing, could limit the operability of fleets. These lower-risk parts can be produced quickly and on-demand, directly at the customer's location, reducing lead times and increasing operational flexibility. By decentralizing part production in this way, Leonardo not only supports the customer's operations but also introduces a more agile, customer-centric supply chain model.

This decentralized, customer-driven manufacturing model not only provides a cost-effective solution but also strengthens customer relationships by offering autonomy and enhanced responsiveness. Leonardo's vision of integrating additive manufacturing in this manner demonstrates their commitment to innovation, operational efficiency, and customer satisfaction.

6.2 Target and objects of interest

Leonardo Aircraft's existing customer base forms the foundation of the potential targets for its new AM support model. As one of the leading Original Equipment Manufacturers in the A&D industry, Leonardo has a broad and diverse network of clients who rely on its products and services to maintain operational efficiency. This business model presents a compelling solution for these customers, particularly those who operate aircraft fleets across various geographical locations and often need rapid access to spare parts. The decentralized nature of this approach allows clients to produce the required components directly at their operational bases, eliminating long lead times and reducing the dependency on traditional supply chain networks. This is especially beneficial in an industry where aircraft downtime can be extremely costly, and swift access to spare parts is crucial for maintaining operational readiness.

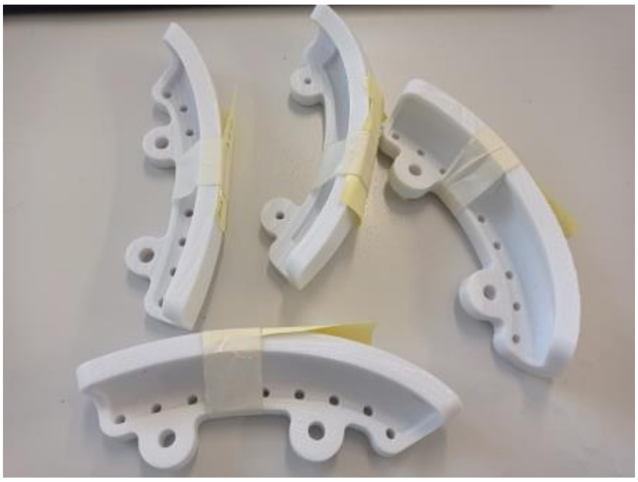


By offering additive manufacturing systems on a lease basis, Leonardo provides its customers with the capability to produce a wide range of spare parts on-demand. The focus is primarily on non-critical components, such as buttons, knobs, and other simple consumable parts that can be produced using Fused Filament Fabrication (FFF) technology. These are typically items that do not require extensive certification or compliance with strict regulatory standards, making them ideal candidates for localized production. Consumable items, such as covers, brackets, and jigs, which are used frequently and often need replacement due to wear and tear, can be produced quickly and efficiently at the client's facilities along with working tools such as holding fixtures, drill/rivet guides, masking tools for paint and sacrificial tools. This not only reduces the need for large inventories of spare parts but also ensures that customers can respond immediately to their own needs without waiting for parts to be shipped from centralized warehouses or production facilities.

Additionally, the flexibility of AM systems allows for the production of larger, more complex parts when necessary. For instance, polymer-based components such as protective covers, can be produced directly on-site. This level of customization and on-demand production enhances the operational flexibility of customers, enabling them to manufacture parts that are specifically tailored to their immediate requirements. This is particularly useful in situations where the standard part might need slight adjustments or modifications to fit a specific use case, something that traditional manufacturing methods would not easily allow.

The model also presents an opportunity to produce tooling and support equipment such as jigs and fixtures, which are essential in maintaining aircraft but are often unique to specific tasks or operations. These parts are generally made from polymer materials that have an available substitute and can be produced using FDM technology. In a traditional setup, these types of tooling would have to be manufactured off-site, resulting in significant lead times and logistic effort. By enabling their production directly at the operational base, Leonardo's clients can ensure that they always have the

Floor cover in red ASA for Typhoon Eurofighter jet



necessary tools available when needed, further minimizing downtime and enhancing the overall efficiency of maintenance operations.

All these parts are to be produced with materials like ULTEM 9085, a certified thermoplastic used in aerospace for its high strength-to-weight ratio and flame-retardant properties. Other materials, such as nylon and polycarbonate, are used to produce tools and jigs that aid in maintenance operations. The flexibility and on-site production capabilities of additive manufacturing greatly benefit Leonardo's customers by allowing for the rapid creation of these components, all while reducing lead times and transportation costs

The approach aligns with current trends in the aerospace industry, where additive manufacturing is increasingly being seen as a means to create more resilient and agile supply chains. The ability to decentralize production and localize it at the point of need provides customers with a significant strategic advantage, particularly in a global context where disruptions to supply chains—such as those caused by geopolitical tensions or pandemics—can have profound effects on operations. By empowering customers to take control of their own spare parts production, Leonardo not only enhances customer autonomy but also strengthens its position as a trusted partner in the industry.

Leonardo Aircraft's additive manufacturing support model targets the operative bases of its customers. The model offers a flexible, decentralized production capability that allows clients to manufacture essential parts directly at their operational bases, reducing lead times, minimizing inventory requirements, and enhancing operational responsiveness. This innovative approach not only improves the customer's ability to manage their supply chains but also reinforces Leonardo's commitment to leveraging advanced manufacturing technologies to enhance its service offerings.

6.3 Service Delivery

The service is designed to provide clients with a high degree of autonomy, while ensuring that the components they manufacture meet the strict quality and performance standards required in these sectors. The service begins with the client having access to a dedicated additive manufacturing facility located at their main operational bases. Additionally, Leonardo ensures that the spools of raw material, essential for the additive manufacturing process, are readily available at these bases, allowing clients to produce parts on-demand.

When a client requires a component or a set of components, a trained operator at the client's facility logs into Leonardo's secure manufacturing system. This system is connected to a digital catalogue developed and maintained by Leonardo, which contains all the necessary manufacturing files for a wide range of components. These files include detailed instructions and procedures for each step of the manufacturing process, from chamber preparation to printing the part to verifying its quality. The catalogue is designed to be comprehensive, providing operators with all the information they need to oversee the production process with minimal external support. Before initiating the printing process, operators have the flexibility to choose how many parts to produce at once, optimizing the use of the available building space. This flexibility is crucial in maximizing efficiency and minimizing downtime, while still adhering to Leonardo's rigorous manufacturing guidelines.

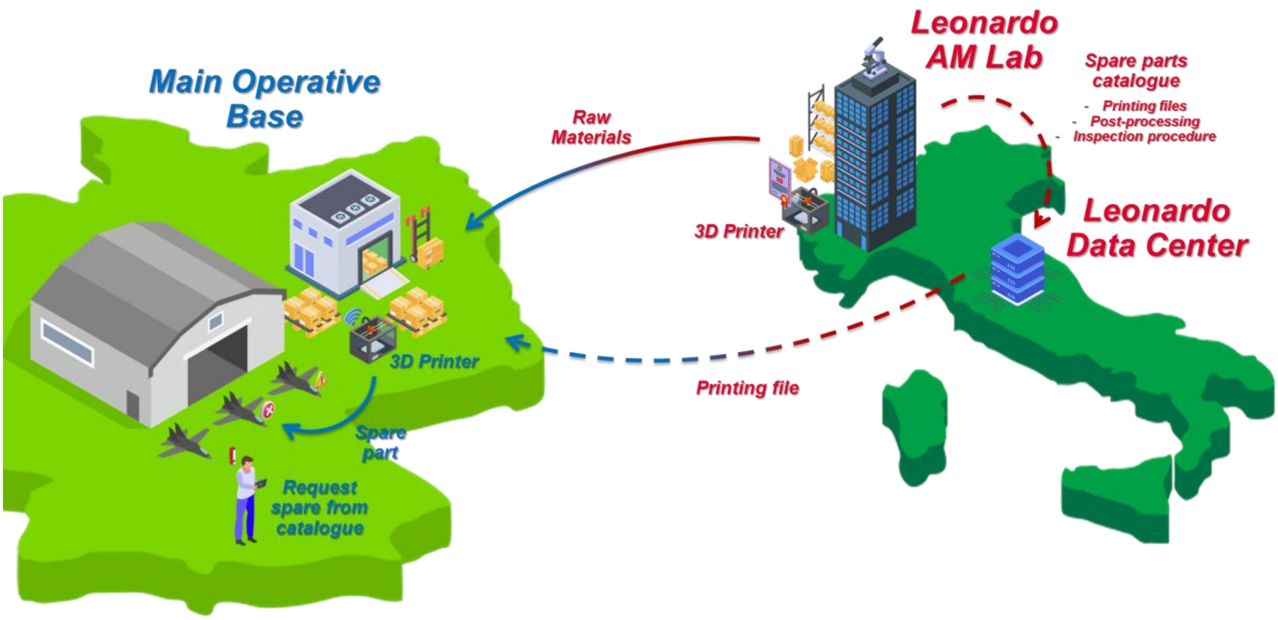
A key aspect of this service model is the relationship between Leonardo and its clients. Leonardo guarantees a certain volume of production each year, following a performance-based approach. This ensures that clients can rely on a steady supply of manufactured parts while allowing Leonardo to meet its commitments. In addition to providing access to the manufacturing system, Leonardo also supplies the raw materials needed for the production process. These materials are delivered directly to the client's facility through a dropshipping model, ensuring that they are always available when needed. The materials provided are rigorously tested and qualified, guaranteeing that the finished components meet the required standards of quality and safety.

To further enhance the service offering, Leonardo actively engages with its clients to continuously improve and expand the digital catalogue. Periodically, the company inquires with its clients about additional parts they would like to see added to the catalogue. This proactive approach ensures that the catalogue remains aligned with the clients' evolving needs and reflects the latest advancements in technology and component design. However, the expansion of the catalogue is not a simple task—it requires Leonardo to develop new manufacturing procedures for each additional part.

Each procedure must be carefully designed and tailored to ensure that the parts can be produced efficiently and with the required quality standards. Once the procedures are developed, everything needs to be rigorously tested in Leonardo’s dedicated additive manufacturing facility. This ensures that each new part added to the catalogue can be consistently manufactured to meet the stringent performance and safety requirements of the aerospace and defense industries.

Through this process of continuous testing and validation, Leonardo can confidently offer a growing range of parts to its clients, while ensuring that the components they produce meet the same standards as those manufactured directly by Leonardo or its suppliers. This collaboration fosters a dynamic and responsive service, helping Leonardo offering clients the flexibility and autonomy they need to manage their own production.

6.4 Resources and Activities



In this chapter the resources necessary for implementing the Support Business model are exposed, along with the necessary activities to start and maintain the project. The main objects are:

- Leonardo AM Lab and Spare Parts Catalogue
- IT infrastructure, embedded within the AM manufacturing systems
- AM manufacturing systems and qualified operators at clients' MOB
- Know-how management (training)

In the following paragraphs detailed overview is provided.

6.4.1 AM Lab and Spare Parts Catalogue

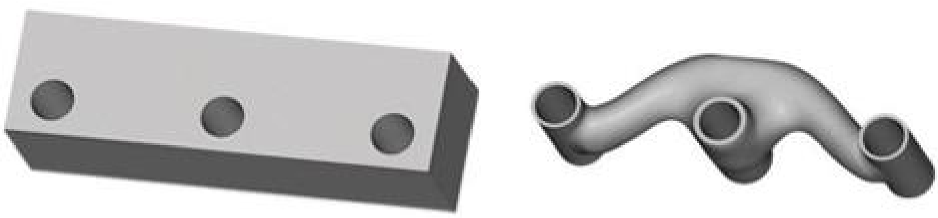
A catalogue of printable parts is developed by engineering. First, a pool of printable parts is selected based on technical, logistical, and economical criteria. Engineering and Logistic are going through a concurrent process to extract economics and logistic information for evaluating the convenience of going through a redesign process and manufacturing procedure qualification. After a raw selection of the candidates, a final selection is done where technical requirements and constraints are considered for evaluating the suitability of every candidate.

After the final selection of candidates is completed, engineering produces what is necessary for a client's operator to manufacture the parts they need in autonomy:

- Printing path
- Manufacturing conditions (i.e. temperature of the chamber, supports removal procedure, post-processing, etc.)
- Quality-check procedures

It is worth noting that AM allows to provide a "click-and-print" solution: what is provided to the clients is not the CAD file, but the Job file (e.g. G-code). This type of files contains all the necessary information for the manufacturing system to produce a job (that is, the printing path and manufacturing conditions).

During this phase all selected candidates go through a process of redesign and qualification. It is in this phase that AM unique benefits can be leveraged at their most: manufacturing with 3D printing



Original design (left) and topology-optimized design (right), courtesy of nTopology removes constraints tied with traditional manufacturing technologies, allowing for weight reduction and topological optimization. As said in previous paragraphs, the whole life cycle of a product is to be considered to evaluate the convenience of additive manufacturing compared to traditional manufacturing. Topological optimization and weight reduction give the opportunity to reduce costs tied to the management of the parts, for example the transportation costs of raw materials are mitigated and the fuel consumption during the life cycle of the products. Topological optimization Is a mathematical approach to determining material location within a part to optimize performance. It uses Finite Elements Analysis (FEA) to determine the state of stress in the part and remove material from low-stress regions to arrive at a lightweight conceptual design.

The generation of the spare parts catalogue requires a lot of effort from Leonardo Aircraft. The main effort is tied to spare parts selection, redesign and qualification and the costs related to these activities are hard to evaluate given the lack of literature and experience in redesign and qualification processes for AM-manufactured components. This opens opportunities for considering innovative approaches and technologies, such as Object Recognition enabled by Artificial Intelligence: the automation of any step of the candidate selection process would have relevant impact on costs and developing time.

The evaluation of parts to be produced via AM revolves around the ERP system of the company. It is necessary to integrate several sets of metadata originated in different units of the company. It is worth mentioning the CALE datasets: I dataset CALE si prefigurano come repository atti a recepire I dati relative alle parti di ricambio del velivolo, le cui informazioni sono presenti nei diversi database aziendali. I dai presenti nel dataset CALE sono suddivisi in quattro macro aree da cui deriva l'acronimo CALE (Configurativo – Affidabilistico – Logitico – Economico).

The initial catalogue obtained is a starting point after which the collaboration of clients is paramount: clients are invited to signal any component that they wish to be able to produce at their operative bases. Considering the wide network and of Leonardo's clients, it is safe to assume that not every client will consider the same parts as relevant to be produced in time and in place: it is important to support a collaboration between Leonardo and its clients to address exactly what are their needs.

6.4.2 IT infrastructure

The manufacturing systems available at the clients' bases are to be connected with the proprietary Leonardo AM platform that allows operators to access the repository containing the manufacturing files. The infrastructure needs to be able to transfer files and usage data to and from the clients without damages and data leaks. The IT infrastructure needs to be developed and embedded within the AM systems, safe and reliable.

6.4.3 AM manufacturing systems

An internal printer is needed for the testing and validation of design, manufacturing files, post- and pre- processing procedures, and quality verification instruction for the parts to be added in the catalogue. Manufacturing systems to be installed the clients' bases are to be purchased and qualified. This hardware is Leonardo's property and at the availability of clients through a performance-based-leasing approach: Leonardo is responsible for installation, maintenance, and the provisioning of all raw materials and eventual consumables needed for the production of a pre-specified amount of jobs for which the clients pay a fixed amount every period.

6.4.4 Training – DfAM: Design for Additive Manufacturing

Engineers must think in a different way when designing for AM: it is possible to concentrate more on functionality and less on manufacturability, given the disruption of the constraints due to traditional manufacturing technologies limitations. Experienced staff can make the difference on the outcome of the activities carried out. The processes of redesign of existing parts and of designing new parts for AM production requires knowledge that goes beyond the knowledge needed for traditional manufacturing so that engineers and operators are going to be subject to a thorough training.

Particularly, Leonardo's engineers shall be trained on Design for Additive Manufacturing (DfAM): DfAM focuses on techniques used to maximize the value of AM for production applications. The technology removes many conventional manufacturing constraints but imposes new ones on its own. Most designers have been educated and trained to focus on traditional manufacturing requirements considerations such as draft angles, wall thickness and geometric simplification, making it difficult to adapt their thinking when designing for AM.

Several overarching design considerations apply to most AM technologies, including the following:

- **Minimize material usage**: any material that do not serve a real engineering function shall be removed. Design to avoid support material.
- **Design with build orientation in mind**: build orientation is among the key factors that determine the orientation of anisotropy, surface finish, location, and amount of required support material.

- **Fillet edges whenever possible**: sharp internal corners can cause stress concentrations and may weaken the part. Sharp external corners are less comfortable to hold and use more material.

Internal knowledge is paramount for leveraging the technology at its full potential. The learning effects over the course of the years allow to fully implement the innovative features of Additive Manufacturing.

6.5 Overview of the Cost Structure

In the context of implementing AMaaS for the provisioning of polymer spare parts and GSE, understanding the cost structure is crucial for assessing the feasibility and sustainability of the business model. This chapter will analyze the different cost components associated with Leonardo's AM services, focusing on the leasing model, where clients pay an annual fee and Leonardo provides everything necessary for production. The cost structure encompasses fixed and variable costs, operational expenses, intellectual property (IP) management, and compliance-related costs. The analysis was developed considering real costs provided by the company, but for understandable proprietary and strategic reasons only a qualitative reporting is exposed in this thesis.

6.5.1 Fixed Costs

Fixed costs represent the stable expenses that do not depend on the number of parts produced. These include the acquisition, setup, and maintenance of hardware, as well as long-term operational requirements.

6.5.1.1 Additive Manufacturing Systems acquisition, installation, and maintenance

Leonardo provides its clients with qualified manufacturing systems, which are either purchased or leased by the company. These machines represent a significant capital investment. The fixed costs associated with these systems include the **purchase or lease** of the equipment from the original manufacturer, the **installation and setup** at the client's operational base, including any required modifications to the facility.

6.5.1.2 Maintenance and Software Licensing

As a part of the service agreement, Leonardo assumes responsibility for ensuring optimal performance of the systems along with the repairs and spare parts required to keep the system running and for providing the specialized software required for managing production and the creation of the build.

6.5.1.3 Training Programs

Operator training is a critical part of ensuring that clients can use the AM systems effectively. Leonardo provides comprehensive training programs for client employees, which may be included in the fixed costs. This training ensures operators are proficient in machine operation, post-processing techniques, and all the safety and compliance requirements.

It is worth mentioning the presence, in many clients' MOBs, of a Field Service Representative (FSR) of Leonardo Aircraft. A FSR is the contact point of Leonardo for the clients and could potentially be a key role for the business model, simplifying communication and support requests.

6.5.1.4 Spare Parts Catalogue Development

Leonardo develops a comprehensive catalogue of spare parts that clients can print on-demand. Each part produced requires detailed design preparation, including the generation of digital models and printing instructions. Leonardo incurs costs related to:

- **Design Optimization**: Preparing part designs for 3D printing, which involves optimizing models to reduce material usage or improve performance.
- **Preparation of Manufacturing Files**: The cost of generating files compatible with the AM systems, which includes slicing files and setting parameters for each print job.
- **Testing and Validation**: Testing may be conducted to ensure that the design will meet performance requirements.
- **Catalogue Upkeeping**: Regular updates to the catalogue following clients' requests, ensuring that new parts are added, and obsolete parts are removed or revised.

6.5.2 Variable Costs

Variable costs fluctuate based on the number of parts or jobs produced. These costs are directly tied to the production volume and the type of parts being printed.

6.5.2.1 Raw Materials

The primary variable cost is the provisioning of raw materials. For polymer components, it typically involves standard MEX (Material Extrusion) polymers such as ABS, high performance thermoplastics such as ULTEM®, PC or Nylon, and the materials for building supports, along with consumables such as washing chemicals.

The Performance-Based Approach adopted by Leonardo plays a pivotal role in managing raw material costs. Since the number of jobs or parts to be produced is predetermined in the service agreements, Leonardo can accurately forecast the amount of raw materials required for production. This predictability allows the company to plan procurement in advance, securing materials at stable prices and mitigating the risks of market fluctuations.

In this approach, raw materials are no longer a volatile variable but rather a well-managed, predictable component of the overall cost structure. The ability to align material procurement with the expected production volume not only enhances cost efficiency but also strengthens the reliability and responsiveness of the Customer Support service.

The company could also consider maintaining an internal warehouse for AM raw materials for internal production and validation and as a mitigator for suppliers-related risk: Leonardo would be able to fulfill shortages or delayed procurement caused by the qualified suppliers. The combination of dropshipping from qualified suppliers and a proprietary Leonardo's warehouse allow for a resilient provisioning chain, reducing the effects of externalities.

6.5.2.2 Logistics and Supply Chain

The delivery of raw materials to the client's facility falls under variable logistics costs. This includes the costs for material shipping, that may vary depending on the location of the customers' operative bases, and warehousing costs.

6.5.3 Compliance and Certification Costs

Leonardo's cost structure must accommodate a variety of expenses related to ensuring that its AM processes, materials, and final products meet these stringent regulatory standards. Additive manufacturing (AM) introduces unique challenges and opportunities when it comes to meeting these industry requirements such as the AS9100 Certification and the NADCAP Accreditation.

The AS9100 certification is the internationally recognized Quality Management System (QMS) standard for the aerospace industry (*IAQG. (2016). AS9100D Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations.* Available at: https://www.sae.org/iaqg/) while the National Aerospace and Defense Contractors Accreditation Program (NADCAP) sets industry standards for specific processes such as welding, coatings, and now additive manufacturing (*Performance Review Institute. (2020). NADCAP Accreditation Overview.* Available at: https://p-r-i.org/nadcap/).

One of the most critical components of compliance costs is related to the validation and certification of each part produced via additive manufacturing due to its state of being a Special Process under Leonardo's Quality Management System. which means every part must undergo thorough testing and certification before it can be deployed.

6.5.4 Miscellaneous Costs

Among the costs for the maintenance of the project, Leonardo may need to cover the cost of ensuring the additive manufacturing systems and the parts produced: equipment breakdowns or damage that may occur during operation, and defects in manufactured parts or failures can lead to operational issues for clients.

Also, to remain competitive in the rapidly evolving field of additive manufacturing, Leonardo invests in R&D. These costs involve investigating new polymers or composite materials for AM applications or exploring new methods to improve the efficiency and quality of additive manufacturing processes.

6.6 Revenue Structure: The Performance-Based Payment Model

In the current landscape of aerospace and defense industries, cost predictability and operational efficiency are paramount. Leonardo's adoption of a performance-based approach (PBA) for additive manufacturing services seeks to address these needs. Unlike traditional pay-per-use models, the PBA provides clients with a fixed annual fee covering all production-related costs, ensuring that the client's spare parts production remains uninterrupted while enhancing cost predictability.

The cornerstone of this model is the fixed annual fee, paid by the client to Leonardo. This fee covers all aspects of additive manufacturing for a predetermined number of jobs or parts. By agreeing on this number ahead of time, both parties achieve clarity and predictability in costs and services. The fee is structured to include hardware use, material supply, operator training, and maintenance of the additive manufacturing systems. This fixed fee allows clients to simplify budgeting, as they know their production costs upfront without worrying about variable expenses such as breakdowns or unexpected material shortages.

6.6.1 Cost Components Included in the Fixed Fee

As part of the PBA, Leonardo provides and installs the 3D printers necessary for production, with the cost of leasing included in the fixed fee. This model removes the capital investment burden from clients and allows them to focus on operations rather than managing expensive equipment. Maintenance and system updates are Leonardo's responsibility, ensuring maximum equipment uptime and performance.

Leonardo provides all the software licensing and raw materials needed for additive manufacturing, from polymers to any other necessary materials. By bundling this into the annual fee, Leonardo absorbs the risk of price fluctuations in raw material markets, simplifying cost management for clients.

Operator training is included as part of the fixed fee, ensuring that the client's workforce is skilled in using the additive manufacturing systems. Ongoing technical support is also provided to troubleshoot issues and ensure smooth operation.

6.6.2 Performance-Based Service Level Agreement (SLA)

At the core of the PBA is the Service Level Agreement (SLA), which establishes the expected number of jobs or parts to be produced annually. Leonardo guarantees that all necessary resources—additive manufacturing hardware, materials, and operator support—will be provided to meet this target.

The SLA includes:

- **Quality Assurance Benchmarks**: all parts must meet the required standards for performance and durability
- **Uptime Guarantees**: Leonardo commits to maintaining high availability for the additive manufacturing systems.
- **Production Time Guarantees**: Leonardo ensures that parts are produced within a certain timeframe

The fixed annual fee is based on a predetermined number of jobs or parts. However, if the client's needs exceed this number, overage charges are applied. These charges are predefined in the contract, ensuring transparency and preventing unexpected costs. This flexibility allows clients to adapt their production needs without renegotiating the entire agreement.

If a client anticipates a significant change in their production volume, they may renegotiate the annual fee or adjust the terms of their SLA. This flexibility ensures that both parties can adapt to changing circumstances while maintaining the stability of the partnership.

6.6.3 Cost Transparency and Client Benefits

One of the key benefits of the performance-based approach is cost predictability. Clients know the exact amount they will pay each year, which simplifies budgeting and allows for more accurate financial planning.

With the PBA, Leonardo is incentivized to optimize production and minimize waste. Since Leonardo absorbs the costs of material use and machine maintenance, the company benefits from finding more efficient ways to meet production goals. This efficiency drives innovation and cost reduction, ultimately benefiting both Leonardo and its clients.

6.6.4 Value Proposition for Both Parties

For clients, the PBA offers:

- **Cost Stability**: A fixed fee ensures that production costs remain consistent throughout the year.
- **Simplified Operations**: Leonardo takes care of equipment, materials, and technical support, allowing clients to focus on their core operations.
- **Guaranteed Output**: Clients have confidence that their production needs will be met, with the assurance of high-quality parts delivered on time.

For Leonardo, the PBA creates opportunities for:

- **Operational Control**: By managing the entire production system, Leonardo can continuously improve processes and reduce costs.
- **Long-Term Partnerships**: The PBA fosters stronger, longer-term relationships with clients, creating a steady revenue stream.
- **Scalable Revenue**: As client needs grow, Leonardo can scale its services without renegotiating every detail, increasing efficiency and profitability.

6.7 Cost Study - Qualitative Approach

Due to the high strategic importance and confidentiality surrounding the structural costs of Leonardo, the results of this cost study are presented on a qualitative basis. This study provides a detailed estimate of potential costs using internal information and the expertise of Leonardo's engineers. The following sections explain the methods and approach taken to estimate the costs associated with the implementation of additive manufacturing for the production of spare parts. Although numerical results cannot be disclosed, the conceptual framework remains integral to understanding the financial impact of this initiative.

6.7.1 Starting Costs

Starting costs represent the upfront investments necessary to launch the AM project, particularly in terms of hardware acquisition, catalogue development, and IT infrastructure. These costs are non-recurring, fixed, and largely sunk, as they cannot be recuperated after the initial investment.

Selection of First Candidates for the Catalogue

The first version of the spare parts catalogue requires a collaborative effort between Engineering, Logistics Engineering, and Purchasing. The selection of parts for the AM process involves a detailed opportunity analysis, which evaluates the full life cycle of each component to determine the feasibility of redesigning them for AM.

- **Methodology**: Cost estimates were based on the evaluation of each component, using fixed time frames for assessments and a calculated success rate (ratio of components that pass evaluation). The goal was to identify 100 parts for the initial catalogue.
- **Cost Characteristics**: These costs are non-recurring, fixed, and sunk, as the effort is only required for the initial catalogue and does not vary with production volume. Once spent, these costs cannot be recuperated.

Development, Testing, and Approval of Production Procedures

Once selected, parts undergo a redesign to optimize them for AM. This involves both destructive and non-destructive testing to validate the manufacturing processes.

- **Methodology**: The cost estimation involved assigning fixed times for redesign and validation, as well as accounting for material costs, with a margin added due to the variability and non-standardized nature of early production processes.
- **Cost Characteristics**: These are non-recurring, fixed costs, covering both the redesign efforts and testing procedures. While the material costs for testing are variable, a conservative estimate with a safety margin was applied.

Development of IT Infrastructure

A robust, secure IT infrastructure is critical for facilitating the transfer of digital manufacturing files between Leonardo and client bases. Two solutions were considered: a real-time connection for locations with stable access, and an offline system for remote locations or those with limited connectivity to Leonardo's servers.

- **Methodology**: For cost estimation, the more realistic scenario of outsourcing IT development to trusted consultants was assumed. A fixed, non-recurring lump sum was applied, representing the investment required for developing a scalable platform.
- **Cost Characteristics**: These costs are fixed, sunk, and non-recurring, as the infrastructure is designed for long-term use, and cannot be recovered once deployed.

Internal AM Hardware Integration and Qualification

To validate the manufacturing procedures, Leonardo acquired an AM system. This AM system is a robust and reliable professional hardware/software solution proposed by an established global leader in the field of FFF technologies. While the initial purchase cost is non-sunk, only the depreciation cost is considered in this study. Other costs, such as system qualification and IT integration, are sunk and non-recurring.

- **Methodology**: The cost estimation for integration and qualification was based on the efforts required for hardware setup, testing, and IT system integration.
- **Cost Characteristics**: Depreciation is calculated based on a linear amortization over five years, while the qualification costs are considered sunk.

6.7.2 Annual Fixed Costs

Annual fixed costs are incurred every year, regardless of the number of clients or parts produced. These costs are largely sunk and represent the ongoing expenses required to maintain the AM project.

Depreciation of Internal AM Hardware

The AM system, while purchased upfront, incurs depreciation over time.

- **Methodology**: Depreciation is calculated based on the acquisition cost, residual value, and a linear amortization over five years.

- **Cost Characteristics**: Depreciation is a fixed, sunk cost as it is based on the initial hardware investment and is incurred annually.

Evaluation of Catalogue Update Requests

After the initial catalogue is developed, Leonardo actively engages with clients to gather feedback and identify additional parts to add to the catalogue.

- **Methodology**: The costs for evaluating update requests are estimated using the same methodology as for the initial catalogue development—fixed time per evaluation, success rates, and a goal for the number of parts added annually.
- **Cost Characteristics**: These costs are fixed and recurring but sunk, as they do not depend on production volumes.

Development, Testing, and Approval of Manufacturing Files for New Catalogue Items

New parts that are approved to be added to the catalogue go through the same redesign and testing process as those in the initial catalogue.

- **Methodology**: The same cost estimation methods used for the original production procedures are applied here, with estimates based on expected volumes of update requests.
- **Cost Characteristics**: These costs are fixed and recurring, tied to client engagement and new parts requests.

IT Infrastructure Maintenance

Maintaining the IT infrastructure is an ongoing requirement, ensuring that the platform remains secure and functional for both real-time and offline connections.

- **Methodology**: The cost of IT maintenance is estimated as a percentage of the initial development cost.
- **Cost Characteristics**: These costs are fixed, recurring, and sunk, as they do not vary with the number of clients or parts produced.

Maintenance and Licenses – Internal AM Hardware

The AM system requires regular maintenance and software license renewals.

- **Methodology**: Cost estimates for maintenance and software licensing were provided by an established global leader in the field of FFF technologies., with annual fixed costs allocated to this category.

- **Cost Characteristics**: These costs are fixed, recurring, and sunk.

6.7.3 Costs for Each New Client

The following costs are incurred whenever a new client is onboarded to Leonardo's AM system. These are non-recurring and fixed, applying only once per client.

Client's AM Hardware Integration and Qualification

The AM system acquired for each client needs to be qualified and integrated with the IT infrastructure.

- **Methodology**: The cost estimation reflects the efforts needed to qualify and integrate the hardware at the client's base.
- **Cost Characteristics**: These costs are non-recurring, fixed, and specific to each client.

Training of Client's Operators

Leonardo provides training to client operators to ensure they can use the AM systems effectively.

- **Methodology**: The cost of operator training was estimated based on historical training costs and the number of trainees per client.
- **Cost Characteristics**: These costs are non-recurring, fixed, and sunk for each new client.

6.7.4 Annual Fixed Costs for Each Client

These costs are tied to the ongoing maintenance and support of each client's AM hardware and production capabilities.

Depreciation of Client's AM Hardware

Each client is provided with a manufacturing system, which is owned by Leonardo and depreciated over time.

- **Methodology**: Depreciation is calculated similarly to the internal hardware, using the acquisition cost, residual value, and a five-year amortization period.
- **Cost Characteristics**: Depreciation is a fixed, sunk cost incurred annually for each client.

Maintenance and Licensing of Client's AM Hardware

The AM system at the client's base requires regular maintenance and software updates.

- **Methodology**: Maintenance and licensing costs were provided by Stratasys®, with annual fixed costs per client.
- **Cost Characteristics**: These costs are fixed, recurring, and sunk.

Provision of Raw Materials for Client's Production

Leonardo is responsible for providing raw materials to each client, guaranteeing enough material to produce a predetermined number of parts each year.

- **Methodology**: The cost estimation for raw materials is based on the maximum printable material for a single job, including a margin for transportation and material wastage. Material costs were provided by Stratasys®.
- **Cost Characteristics**: These costs are fixed for each client but vary based on the volume of jobs guaranteed per year. However, within the guaranteed production limits, they are predictable due to the performance-based approach.

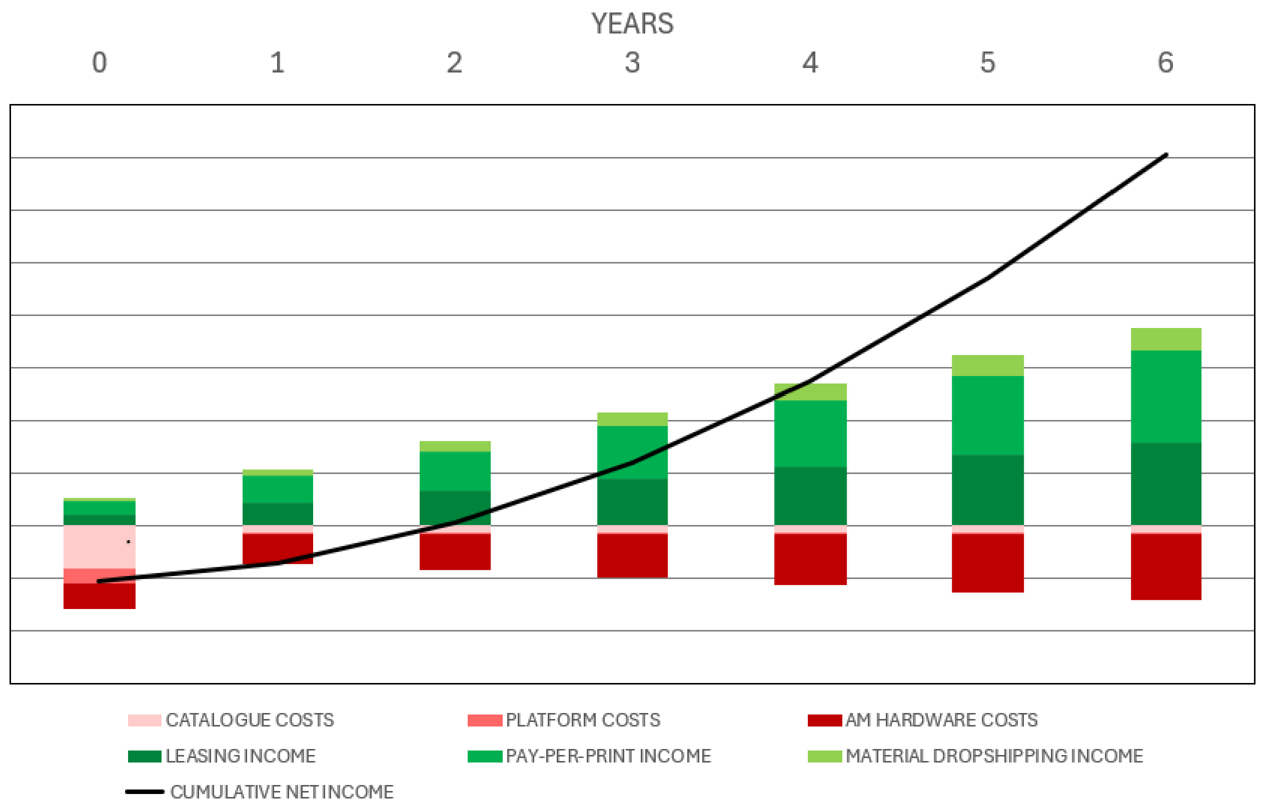
6.7.5 Summary and Analysis of the Results

The table below summarizes the cost items, the characteristics, and the calculation method used for this evaluation. For representation purposes, cost items were grouped into three categories:

- **Catalogue Costs (CC):** These costs are primarily upfront and associated with the development of the initial version of the spare parts catalogue. They gradually reduce as updates and maintenance efforts become the focus after the initial investment.
- **Platform Costs (PC):** These costs represent the expenses related to the development of the IT infrastructure, including software, network security, and system integration. They peak in the early years due to the initial setup, then stabilize as only maintenance costs remain in the later years.
- **AM Hardware Costs (AHC):** This includes the depreciation of hardware such as 3D printers and related machinery, as well as qualification and training for maintaining the production operational. These costs remain consistent over time, reflecting a steady depreciation schedule.

	COST ITEM	CHARACTERISTICS	CALCULATION METHOD	CATEGORY
1	Selection of First Candidates	Fixed, non-recurring, sunk	Based on fixed time per component evaluation	CC
2	Development, Testing, and Approval of Production Procedures	Fixed, non-recurring, with margin for variability	Assigned fixed time per part and material cost with safety margin	CC
3	Development of IT Infrastructure	Fixed, non-recurring, sunk	Fixed lump sum for outsourced IT development	PC
4	Internal AM Hardware Integration and Qualification	Fixed, non-recurring, partly sunk	Effort-based estimation	AHC
5	Depreciation of Internal AM Hardware	Fixed, non-recurring, sunk	Depreciation based on acquisition cost and linear amortization over 5 years	AHC
6	Evaluation of Catalogue Update Requests	Fixed, non-recurring, sunk	Identical to first catalogue development	CC
7	Development, Testing, and Approval of New Manufacturing Files	Fixed, recurring, based on client requests	Identical to first catalogue development with percentage estimate of new parts	CC
8	IT Infrastructure Maintenance	Fixed, recurring, sunk	Percentage of initial development cost	PC
9	Maintenance and Licenses – Internal AM Hardware	Fixed, recurring, sunk	Costs provided by Stratasys®	AHC

10	Client's AM Hardware Integration and Qualification	Fixed, non-recurring, client-specific	Effort-based estimation for hardware integration	AHC
11	Training of Client's Operators	Fixed, non-recurring, client-specific	Historical costs for operator training	AHC
12	Depreciation of Client's AM Hardware	Fixed, recurring, sunk	Depreciation based on acquisition cost and linear amortization over 5 years	AHC
13	Maintenance and Licensing of Client's AM Hardware	Fixed, recurring, client-specific	Costs provided by Stratasys®	AHC
14	Provision of Raw Materials for Client's Production	Variable, based on production volume, predictable	Estimated max printable material per job plus margin for transport and wastage	AHC



The graph presented provides a qualitative illustration of the costs and revenue streams projected over a 6-year period for the implementation of the model presented. It also includes the cumulative net income trajectory, reflecting how costs and revenue interact to drive long-term profitability.

Revenue comes from a fixed fee that clients pay annually, but for clarity purposes it was also grouped into three categories:

- **Leasing Income:** This represents the fixed annual revenue generated from leasing the AM hardware to clients. It shows a steady increase, driven by the onboarding of new clients over time.
- **Pay-per-Print Income**: This revenue comes from the actual use of the AM system by clients. It fluctuates based on client demand but shows a steady rise as more parts are printed each year.
- **Material Dropshipping Income:** This represents revenue from selling raw materials to clients for use in the AM systems. It is expected to grow steadily, correlating with the increase in printed parts by clients.

The black line represents the aggregate profit over time, combining all costs and revenue streams. Initially, the costs exceed the revenue, resulting in a net loss. However, as the revenue from leasing, printing, and material sales grows, the cumulative net income turns positive around year 3 or 4, illustrating the point where the business model becomes profitable.

The early years are characterized by significant upfront costs, particularly in platform development, hardware acquisition, and catalogue creation. While some revenue is generated through leasing, the cumulative net income remains negative during this phase.

By year 3, costs start to stabilize as the infrastructure and initial catalogue are fully established. Revenue from pay-per-print and material sales begins to grow steadily, pushing the cumulative net income toward profitability.

In the later years, the costs stabilize, while revenues continue to increase with client usage and material sales. The cumulative net income reflects a positive trend, indicating the long-term financial sustainability of the Support business model.

Chapter 7: Discussions and Conclusions

7.1 Strengths and Weaknesses

The implementation of additive manufacturing as a service in the customer support, as developed by Leonardo, presents significant strengths but also challenges. particularly in terms of costs, technological reliance, and certification requirements.

7.1.1 Strenghts

One of the primary strengths of this model lies in its ability to offer **cost predictability**. By adopting a performance-based approach with fixed annual fees, Leonardo enables clients to manage their budgets more effectively. Clients are aware of their yearly expenses without worrying about fluctuating costs related to maintenance, material procurement, or equipment breakdowns. For Leonardo, this model also provides predictable revenue streams, which helps with long-term financial planning and resource allocation.

Another advantage is in **material provisioning**. The predetermined number of parts or jobs required allows Leonardo to forecast raw material needs with precision. This not only reduces the risk of material shortages but also helps the company negotiate better rates for materials by planning procurement ahead of time. By doing so, the company ensures steady operations, balancing cost control with supply chain efficiency.

The model also demonstrates **flexibility and scalability**. Clients have the ability to produce parts as needed, which reduces the need for excessive inventory and offers greater responsiveness to operational demands. Additionally, Leonardo's IT infrastructure is designed to cater to different client needs, offering both real-time connections and offline solutions depending on the client's logistical situation. This flexibility enhances the model's appeal to a wide variety of clients in different geographical regions.

In terms of **client relationships**, the business model fosters long-term partnerships. By leasing AM hardware and offering ongoing services such as maintenance, operator training, and material provisioning, Leonardo positions itself as a critical part of its clients' production processes. This deep integration makes it more difficult for clients to switch to competitors and solidifies the company's role as a trusted partner.

Another strength lies in Leonardo's ability to comply with stringent aerospace and defense certification requirements. The AM processes are developed to meet rigorous standards such as AS9100 for quality management and NADCAP accreditation for process-specific requirements like non-destructive testing (NDT) and material verification. These certifications are crucial for operating in the aerospace sector, where safety and reliability are paramount. Leonardo's ongoing investments in meeting these certification standards enhance its credibility and enable it to serve highly regulated industries. Meeting these standards not only ensures compliance but also positions Leonardo as a trusted partner in the aerospace supply chain.

Finally, the model promotes **innovation and continuous improvement**. By encouraging client feedback to update the parts catalogue, Leonardo ensures that the service evolves alongside client needs and industry standards. The ability to respond dynamically to market changes positions Leonardo as a forward-thinking player in the AM space. As shown in the revenue projections, the model has the potential for long-term profitability, once the initial high costs have been amortized and the revenue streams stabilize and grow.

7.1.2 Weaknesses

Despite its strengths, the model also faces several challenges. One of the primary weaknesses is the **high initial capital investment** required to launch the AM business. Significant upfront costs are incurred in hardware acquisition, IT infrastructure development, and catalogue creation. These costs are largely sunk, meaning they cannot be recovered if the business underperforms. Although depreciation spreads out hardware costs over time, the early financial burden and capital expenditure is substantial. Moreover, the initial parts catalogue requires extensive input from multiple departments, such as Engineering, Logistics, and Purchasing, which can lead to delays in time-to-market and strain internal resources.

Another key weakness is the **uncertainty surrounding client adoption**. While the model's leasing and pay-per-print structure has the potential to generate consistent revenue, it relies heavily on clients' willingness to adopt the AM technology. Aerospace clients, in particular, tend to be cautious when integrating new technologies into their operations. This conservatism could result in slower-than-expected adoption rates, which would affect revenue growth and delay the realization of return on investment.

In addition, the company must navigate **risks related to raw material provisioning**. Although Leonardo can forecast material needs due to the fixed number of jobs, unexpected increases in material costs or supply chain disruptions could still impact profitability. Since Leonardo is responsible for sourcing and delivering these materials to clients, any supply chain inefficiencies could lead to delays or increased operational costs, particularly when serving clients in remote or international locations.

The model's heavy **dependence on technology** introduces further risks. Maintaining the AM hardware is critical for ensuring uninterrupted production, yet any significant equipment failure or unplanned maintenance could lead to production downtime for clients. This not only disrupts the client's operations but could also damage Leonardo's reputation. Likewise, the IT infrastructure supporting the AM process must remain secure and reliable. Any cybersecurity breaches, system failures, or connectivity issues could compromise production and sensitive data, leading to reputational damage and potential financial losses.

Finally, **meeting the evolving certification standards** presents an ongoing challenge. Aerospace and defense industries are highly regulated, and staying compliant with evolving standards and requirements for additive manufacturing involves significant ongoing costs. Leonardo must continuously invest in maintaining certifications, updating its processes, and undergoing frequent audits. This is particularly true for parts produced using AM, as the qualification of these parts often involves extensive destructive and non-destructive testing to verify structural integrity and material quality. The complexity of complying with these stringent standards could lead to higher operational costs and delays in bringing new parts to market.

Another concern relates to **market competition and rapid technological change**. As the AM industry continues to expand, more competitors are likely to enter the market, offering similar services or more advanced technologies at potentially lower prices. Additionally, the pace of technological advancement in AM, including innovations in materials and printing techniques, could outpace Leonardo's investments, leading to the risk of obsolescence if the company is unable to keep up with new developments.

7.2 Conclusions

Leonardo's additive manufacturing business model demonstrates significant strengths, including cost predictability, scalability, and long-term client engagement. The company's commitment to complying with aerospace and defense certification standards, such as AS9100 and NADCAP, further strengthens its position in this highly regulated industry. However, the model also faces notable challenges, such as high upfront costs, uncertain client adoption, technological dependencies, and the need to continuously meet evolving certification requirements. By addressing these weaknesses through careful planning, continued innovation, and strategic risk management, Leonardo can capitalize on the growing potential of additive manufacturing while ensuring its long-term success. Leonardo's additive manufacturing (AM) business model highlights significant strengths in cost predictability, scalability, and long-term client engagement. The model's design supports flexible production, aligning with industry standards and ensuring compliance with stringent aerospace and defense certification requirements, such as AS9100 and NADCAP. This commitment to regulatory compliance enhances Leonardo's position in a highly regulated industry, allowing it to leverage AM's advantages while maintaining quality and safety standards essential to the Aerospace and Defense sectors. However, the model encounters several notable challenges, including high initial investments, dependencies on client adoption, and the need to continuously innovate and meet evolving certification requirements.

A major challenge in implementing AM, particularly for the production of spare parts and Ground Support Equipment (GSE), lies in the creation and management of the spare parts catalogue. Currently, evaluating whether a specific part can and should be produced with AM is conducted on a one-to-one basis, which involves assessing each part individually in terms of technical feasibility, economic viability, and logistical considerations. This individualized approach is resource-intensive, costly, and limits scalability, as it requires significant time and specialized expertise for each evaluation. Although past research has provided guidelines for assessing AM feasibility, the lack of a streamlined process for high-volume assessment hinders Leonardo's ability to efficiently expand its catalogue of AM-compatible parts.

7.3 Recommendations for Future Improvements

Addressing the catalogue creation challenge is essential to fully leverage AM's potential and improve its operational scalability. To this end, implementing an automated, data-driven approach to part selection and feasibility analysis would be a transformative step. Specifically, a centralized, AI-enabled system that can perform automated assessments based on predefined criteria—such as material compatibility, design complexity, expected demand, and logistical impact—would facilitate a more scalable and efficient evaluation process.

This enhanced process would allow for faster, cost-effective expansion of the AM-compatible parts catalogue, while reducing reliance on labor-intensive, manual assessments. Integrating machine learning algorithms capable of analyzing historical data, material properties, and part usage patterns could improve decision-making, enabling a more predictive approach to part selection and reducing the time needed to add new parts to the catalogue. Such a system could also support real-time updates and adjustments to the catalogue as new technologies and materials become available, ensuring that Leonardo remains at the forefront of AM innovation.

7.3 Future Outlook

In the longer term, advancing automation in the part selection process will be key to achieving a more agile, on-demand production model. Beyond catalogue creation, Leonardo could consider integrating automated systems into other stages of the AM production cycle, such as material selection, quality control, and supply chain management. Developing a network of certified suppliers and possibly decentralizing certain production activities to client locations could further enhance responsiveness, reduce lead times, and support Leonardo's strategic goals of flexibility and resilience.

Ultimately, by addressing these challenges and embracing data-driven, automated processes, Leonardo stands well-positioned to harness the transformative potential of additive manufacturing. This approach not only supports the company's commitment to cost-effective, on-demand production but also reinforces its alignment with sustainability objectives, such as waste reduction and reduced emissions in line with the European Green Deal. Through continued innovation and strategic adaptation, Leonardo can fully realize AM's benefits, ensuring its long-term success in the rapidly evolving Aerospace and Defense sectors.