

# 3D PRINTING WITH BLOCKCHAIN RELEASED CERTIFICATES IN THE AVIATION INDUSTRY

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Provas para a obtenção do grau de:  
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### *Abstract*

*3D printing and DLT's (Distributed Ledger Technologies) like blockchain are technologies that are gaining more and more importance, nowadays, in the most diverse areas and industries. In aviation both are already being used, although separately. The aim of this work is to understand how the two technologies can be associated to allow manufacturers to produce and certify components, studying all the existing requirements. By printing components and providing the certificates through blockchain, manufacturers' time and resources will be monetised as they will not have to rely on their stock. Consequently, the time that planes are inoperable because they are waiting for a component to be replaced is minimised and the whole process will be faster and more secure.*

### **Keywords**

*Blockchain, 3D Printing, Aeronautical Manufacturing.*



### Resumo

Impressão 3D e DLTs (Distributed Ledger Technologies) como a *blockchain* são tecnologias que estão a ganhar cada vez mais importância nas mais diversas áreas e indústrias. Na aviação ambas estão já a ser utilizadas, embora separadamente. Esta dissertação tem como objetivo perceber de que modo as duas tecnologias se podem associar para permitir aos fabricantes a produção e certificação de componentes, analisando para tal todos os requisitos existentes. Ao imprimir componentes e fornecer os certificados através de *blockchain*, o tempo e os recursos dos fabricantes serão rentabilizados, dado que podem produzir diretamente os materiais, reduzindo a sua dependência de terceiros. Consequentemente, o tempo que as aeronaves ficam inoperacionais por estarem à espera de que um componente seja substituído é minimizado e todo o processo será mais rápido e seguro.

No setor aeronáutico, o processo de aquisição de componentes passa por contactar o fornecedor - que geralmente é o fabricante da aeronave ou do próprio componente - , proceder ao pagamento e aguardar o envio e receção do mesmo. Para além disso, e tão importante quanto a chegada do componente, é a documentação que o acompanha, nomeadamente um certificado (por exemplo EASA Form 1, FAA Form 8130-3) em papel, assinado por uma entidade e pessoa que certificam o componente como aeronavegável. Sem este certificado, o componente não pode ser instalado numa aeronave.

O principal objetivo desta dissertação é mostrar a viabilidade da utilização da impressão 3D no setor aeronáutico, nomeadamente no que diz respeito à impressão de peças simples para o interior da cabine (que sendo uma estrutura secundária, não tem impacto tão relevante na segurança). O desenvolvimento destas peças deve, no entanto, ser também alvo de certificação, garantindo ao instalador a aeronavegabilidade do componente impresso e dando-lhe garantias, através desse mesmo certificado e de uma DLT, de que o componente pode efetivamente ser instalado.

Por forma a estudar a viabilidade do projeto e responder ao propósito da investigação foram levantadas as seguintes questões:

- Pode a *blockchain* ser usada para a emissão de certificados aeronáuticos? Se sim, que limitações e vantagens tem?
- Podem as entidades que não detenham o *Type Certificate* de determinado produto emití-lo com a autorização da organização que detém o *Type Certificate*?

De modo a responder às questões de investigação foram definidos os seguintes objetivos de estudo:

- Definir *blockchain* e impressão 3D e avaliar a sua utilidade para os processos logísticos da indústria aeronáutica;
- Identificar o estado-da-arte das duas tecnologias na indústria;
- Analisar a regulamentação europeia acerca da produção e substituição de materiais e o uso de *blockchain* e impressão 3D na aviação;
- Analisar de que modo a *blockchain* associada à impressão 3D pode ser aplicada no setor aeronáutico.

Para a concretização do estudo, tendo como base os pressupostos acima descritos, adotou-se um método dedutivo e uma análise extensiva que visa, através dos resultados, extrapolar para conclusões maiores. Desenvolveu-se um estudo qualitativo com base em análise e confronto documental, regulamentar e técnico dos dados e factos, partindo de uma posição geral em direção a objetivos mais específicos.

Esta dissertação propõe uma solução inovadora, capaz de revolucionar a indústria aeronáutica. Os conceitos abordados não são novos por si só; contudo quando aplicados em conjunto podem potencializar a eficiência e segurança do processo logístico no setor. A tecnologia *blockchain* permite a criação de um registo imutável e descentralizado das transações realizadas, garantindo a confiabilidade das informações envolvidas no processo de emissão de certificados. Além disso, pode também aumentar

a transparência e a rastreabilidade de todo o processo, desde a fabricação da peça por impressão 3D até à sua instalação na aeronave.

Ao imprimir peças de cabine e certificá-las através da tecnologia *blockchain*, o custo de armazenamento das peças irá desaparecer, uma vez que a necessidade de ter as partes em stock será atenuada ao imprimirem as próprias peças segundo este método. Deste modo, a *supply chain* será modificada, criando-se um fluxo entre o fabricante e o cliente, com base nas necessidades do mesmo e recorrendo à estrutura em *blockchain*.

De modo a demonstrar a viabilidade do projeto, um caso geral será apresentado, seguido de dois casos de estudo aplicados a duas companhias aéreas de países e dimensões diferentes, tendo sido estimados os ganhos e custos do projeto em função da quantidade de peças impressas.

As principais conclusões extrapoladas demonstraram que o projeto de impressão 3D em *blockchain* se torna mais rentável em companhias de maiores dimensões, uma vez que são as que experienciam, anualmente, um maior número de assentos inoperacionais devido a peças de cabine danificadas. Um maior número de lugares afetados indica também uma maior necessidade de peças a imprimir e, por sua vez, um retorno do investimento mais rápido quando comparado a uma companhia onde não ocorrem essas situações com tanta frequência.

Nos casos de estudo apresentados a atenção centrou-se na mesa de refeição; contudo, no futuro, seria importante considerar a inclusão de outros componentes de cabine com características semelhantes, tais como apoios de braços ou persianas, que pudessem também ser impressos em 3D e certificados através da *blockchain*. O alargamento do âmbito de aplicação a estes componentes poderia facilitar o processo de substituição de peças danificadas da cabine, tornando-o mais rápido, mais simples e mais económico.

Como investigação futura será importante realizar uma prova de conceito do projeto, colocando-o em prática num caso real de uma companhia aérea. Tal será fundamental para perceber se o impacto desta inovação vai ao encontro do esperado, e se existem

outros fatores importantes que se devem ter em conta. Não sendo o objetivo deste projeto a análise da regulamentação europeia emitida pela EASA (European Union Aviation Safety Agency), compreende-se a importância de envolver uma Part 21 J e G, que, acompanhados por essa agência, melhor poderão definir o caminho da regulamentação dos componentes impressos pelos métodos aqui propostos.

### **Palavras-chave**

Blockchain, Impressão 3D, Fabricação aeronáutica.



## Index

<b>Acknowledgements</b> .....	v
<i>Abstract</i> .....	vii
<b>Resumo</b> .....	ix
<b>Index</b> .....	xiv
<b>Figure Index</b> .....	xvi
<b>Table Index</b> .....	xviii
<b>Abbreviations</b> .....	xx
<b>CHAPTER I- INTRODUCTION</b> .....	1
<b>1.1 Generalities</b> .....	1
<b>1.2 Scope</b> .....	2
<b>1.3 Motivation</b> .....	2
<b>1.4 Objectives and Research Questions</b> .....	3
<b>1.5 Methodology</b> .....	4
<b>1.6 Structure</b> .....	5
<b>CHAPTER II- LITERATURE REVIEW</b> .....	6
<b>CHAPTER III- STUDY DESIGN</b> .....	29
<b>CHAPTER IV- RESULTS</b> .....	53
<b>CHAPTER V- CONCLUSION</b> .....	67
<b>References</b> .....	71



## Figure Index

<b>Figure 1</b> - Literature review scheme .....	5
<b>Figure 2</b> - Types of Manufacturing .....	8
<b>Figure 3</b> - Economy of scale for each manufacturing type .....	9
<b>Figure 4</b> - Classification of 3D printing technologies.....	10
<b>Figure 5</b> - Examples of blockchain applications in the aviation industry .....	17
<b>Figure 6</b> - A-CDM Management .....	23
<b>Figure 7</b> - Blockchain platform for 3D printing .....	25
<b>Figure 8</b> - Aircraft supply chain structure.....	30
<b>Figure 9</b> - Proposal for a Blockchain-based solution for 3D printing in the aviation industry ....	33
<b>Figure 10</b> - Modix BIG-60 V4 Carbon Fiber 3D Printer .....	39
<b>Figure 11</b> - Costs and Gains per printed parts considering a Component Value of 200€.....	53
<b>Figure 12</b> - Costs and Gains per printed parts considering a Component Value of 400€.....	54
<b>Figure 13</b> - Costs and Gains per printed parts considering Component Value of 600€.....	54
<b>Figure 14</b> - Recaro bi-fold table.....	56
<b>Figure 15</b> - SATA's costs and gains per printed parts, disregarding the inflation rate.....	57
<b>Figure 16</b> - SATA's costs and gains per printed parts, considering the inflation rate .....	59
<b>Figure 17</b> - KLM's costs and gains per printed parts, disregarding the inflation rate.....	60
<b>Figure 18</b> - KLM's costs and gains per printed parts, considering the inflation rate .....	61



## Table Index

<b>Table 1</b> - Variable values applied in $Cd(x)$ under the general case. ....	40
<b>Table 2</b> - Variable values applied in $Cc(x)$ under the general case. ....	42
<b>Table 3</b> - Variable values applied in $G(x)$ under the general case. ....	43
<b>Table 4</b> - Variable values applied in $Cd(x)$ under SATA's case. ....	46
<b>Table 5</b> - Variable values applied in $Cc(x)$ under SATA's case. ....	47
<b>Table 6</b> - Variable values applied in $G(x)$ under SATA's case. ....	48
<b>Table 7</b> - Variable values applied in $Cd(x)$ under KLM's case. ....	49
<b>Table 8</b> - Variable values applied in $Cc(x)$ under KLM's case. ....	50
<b>Table 9</b> - Variable values applied in $G(x)$ under KLM's case. ....	51



## **Abbreviations**

**A-CDM** – Airport Collaborative Decision Making

**AM** – Additive Manufacturing

**BTF** – Buy-to-fly

**CM** – Conventional Manufacturing

**CRS** – Certificate of Release to Service

**CV** – Component Value

**DLT** – Distributed Ledger Technology

**EASA** – European Union Aviation Safety Agency

**FAA** – Federal Aviation Administration

**HR** – Human Resources

**IT** – Information Technology

**MRO** – Maintenance Repair and Overhaul

**OEM** – Original Equipment Manufacturer

**SCM** – Supply Chain Management





### CHAPTER I- INTRODUCTION

#### 1.1 Generalities

Distributed Ledger Technology and 3D printing are fast emerging technologies that are gaining significant importance in various areas (Klößner et al. 2020). Individually, they are already being used in the aviation industry. However, if used together, it could help stakeholders to produce and replace damaged airplane parts faster, minimizing costs, aircrafts ground time and optimizing the aviation supply chain. This altogether helps to maximize the economical factor for both airlines and manufacturers (Klößner et al. 2020).

During aircraft operations, the cabin is probably the most visible and more scrutinised area from the aircraft by the passengers. Despite that most of the cabin material is not essential to conduct a safe flight, it is among the most damaged one. When a specific cabin part is damaged beyond repair, usually the aircraft can operate, but, in some situations, it can limit the seat where the damage is and making it unavailable to the customers. Due to the cabin interiors being highly customized in accordance with the operator's standards, the manufacturers don't usually have a high availability of stock for customized parts, so the operators need to wait for it to be produced, which can lead to weeks or months of waiting and flight or passenger constrains like blocked seats or seats without certain functions. To help mitigate this problem, it is proposed in this study to analyse the effectiveness of 3D printing the part and issue its certificate using a blockchain solution. The Distributed Ledger Technologies (DLT) such as blockchain are peer-to-peer networks that continuously share information between members. Each block of the chain connects to the previous one and has a unique hash value as identification and a timestamp. Because of that, the information can't be manipulated or erased, which help the certifying entities access the data and verify the validity of the 3D part provided. These technologies will revolutionise the industry by shortening both the time of inoperation of the aircraft and the one required to the manufacturers to produce the parts needed, making aviation a non-stop operation and ensuring the civil aviation regulatory framework, taking EASA regulations

as guidelines, which requires the issuance of certificates, the traceability and also the immutability. Since the EASA regulations are more restrictive, they will be taken into consideration in this study. Doing so, the results can be extrapolated to other regions and regulatory frameworks.

## **1.2 Scope**

This study mainly addresses the manufacturers that need to produce specific airplane parts to maintain them operational. However, since this research has a revolutionary purpose, it is meant to affect the aviation industry in its general.

The main goal of this study is to explore an innovative and efficient way of applying blockchain associated with 3D component printing in the aviation industry by exploring both concepts separately and studying how they can combine.

## **1.3 Motivation**

The main problem of this investigation lies in the time an aircraft needs to wait for a specific damaged part to be produced. This question arises because, most of the time, the manufacturers don't have them in stock. With this technology, a solution should appear to make this process faster and more effective.

In the aeronautic ecosystem, whenever someone needs a specific component, they have to contact a supplier, usually the manufacturer of the component, ask for it and wait for it to be delivered. That component must be accompanied by a paper certificate, known as Form-One in EASA and Form 8130-3 in FAA. This project is also meant to deal with the lack of documentation that comes with the components. When there is only a paper version of a certificate, it can be challenging to have it delivered to the final customer, which can create delays on the authorization to install a component on an aircraft.

The aim of this study is to analyse the effectivity to use 3D printing to print simple parts, namely of the cabin interior, which are according to the experience, the most

applicable use cases, and use blockchain technology to issue and validate its certification. To accomplish this, manufacturers would use a DLT, which allows information security, to place a certificate that remains forever guaranteeing its security and authenticity.

### 1.4 Objectives and Research Questions

The generic aim of this study is to evaluate the potential for DLT technology and 3D printing in the aviation industry. Besides, the specific objectives include:

- A. Defining blockchain and 3D printing and its significant utilities in the aviation logistics processes.
- B. Identifying what is already known and done until this moment of those appliances in the aviation industry.
- C. Analysing the regulatory framework of the European Union Aviation Safety Agency regarding the production and replacement of materials and the use of blockchain and 3D printing in aviation.
- D. Analysing how blockchain, together with 3D printing, can be applied in the sector.

The questions of investigation are the following:

- Can blockchain be used to issue aeronautical certificates? If yes, what limitations and advantages does it have?
- Can an organization which doesn't hold the Type Certificate of a certain product, produce it with the authorisation of the organisation that holds the Type Certificate?

The research hypothesis is to understand what the European regulations say about the initial questions and, considering that, how we may make the process of replacement and manufacture of aircraft components faster and more efficient.

## 1.5 Methodology

A qualitative study will be conducted based in document analysis and confrontation with regulatory and technical analysis of the data and facts. The method used will be deductive with an extensive analysis which aims to extrapolate larger conclusions through the obtained results.

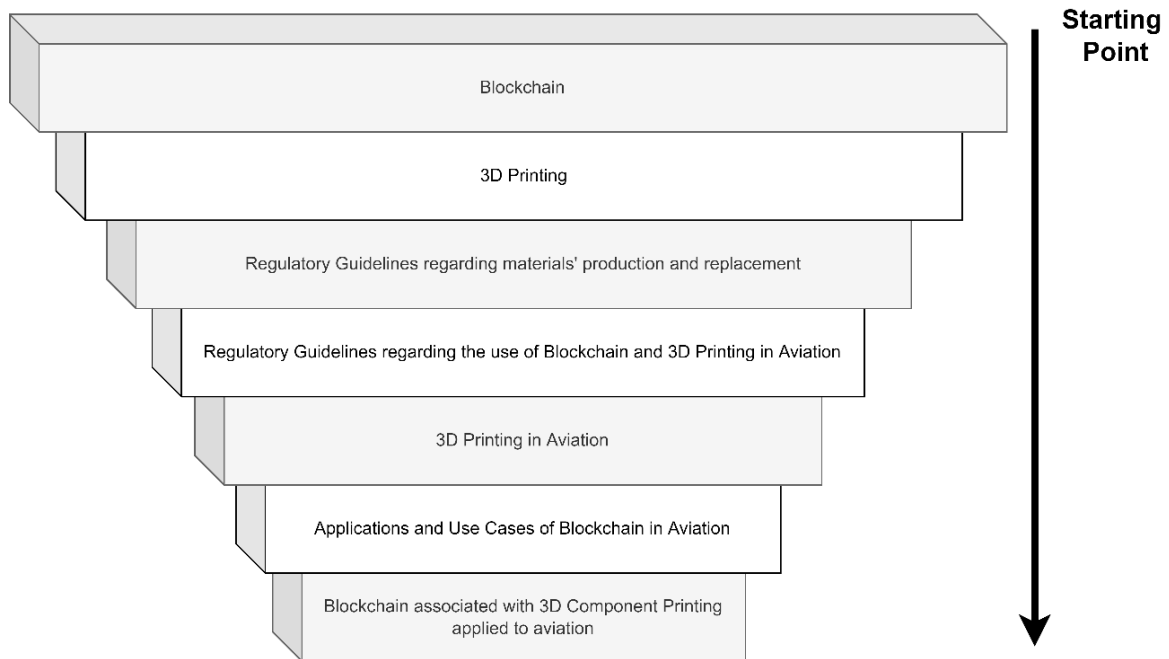
This study is divided into two main parts. First, the literature review will help understand what is already done and researched about the topic in question. After, a description of the project proposed will be done, explaining how it could work regarding the relevant regulation already existent. The questions that will guide the documental analysis will be:

- What are the usages of blockchain in aviation nowadays?
- What are the uses of 3D printing in aviation nowadays?
- What characteristics should 3D printing have in order to ensure its quality and functionality as an aircraft part?
- Can blockchain be used to issue aeronautical certificates? If yes, what limitations and advantages does it have?
- Can an organization which doesn't hold the Type Certificate of a certain product, produce it with the authorisation of the organisation that holds the Type Certificate?

To achieve the design suggested above, the investigation will be conducted based on a pyramid method. As "Pottker (2003) stated, the inverted pyramid method was used by journalists "to strengthen the communicative quality of news" (p.501). It consists of writing in decreasing relevance order, where the most relevant information comes first. (Canavilhas n.d.) In this project, I believe that instead of starting off with the most important topic, beginning with the most generical one will help gathering all the information, contextualization and knowledge needed before proceeding towards the centre of the thesis itself and extrapolating the results. Therefore, conducting the study as shown in Figure 1, will most likely lead to a reliable and achievable outcome, since

the topics of investigation have already been studied and analysed in detail before any conclusions have been drawn. Also, it will help redefine the objectives along the way.

The scheme below illustrates the matters that will be analysed in the literature review, by order:



**Figure 1** - Literature review scheme

**Source:** Elaborated by the author

### 1.6 Structure

This work is divided into five chapters. After defining the purpose and the objectives for this work, it is important to determine how the carried-out research will be presented: In Chapter II a literature review is conducted regarding the state of the art. In the following chapter the design proposed to conduct this study is described. In Chapter IV the results will be presented, going into detail about the meaning of the findings and putting them in context. Following that, in Chapter V the conclusions will be made, as well as a discussion concerning future work needed to be carried out to realize the project as it is presented.

## CHAPTER II- LITERATURE REVIEW

Blockchain is a distributed ledger technology (DLT). A DLT is a decentralised data structure. In other words, it is a database that, instead of being maintained in a single location, the information stored is continuously shared between all the network's nodes. According to Nofer et al. (2017), these technologies are "attracting massive attention and trigger multiple projects in different industries" (p.183), primarily because of cryptocurrencies like Bitcoin.

The origins of blockchain can be traced back to 1991 with the publication of a work done by Stuart Haber and W. Scott Stornetta about cryptography secured chains of blocks. One year after, "they incorporated Merkle trees into the design allowing several documents to be collected into a block", but it was only until 2008 when this technology gained significant importance, due to Satoshi Nakamoto's publication of the Bitcoin white paper (Tijan et al., 2019, p.2). Blockchain is a chain of blocks containing data in which each block has a unique hash value and a unique timestamp to keep the information secured. This way, every change in the chain's blocks does also provoke a change in its hash to prevent frauds from occurring (Nofer et al. 2017). Another significant characteristic of this chain is its decentralisation since there is no physical database that can easily be erased. This occurs because the network is exclusively run by its members (Tijan et al., 2019). To add data, it must be shared with all the associates of the peer-to-peer network, each one keeping a local copy of it. There are also no external intermediaries needed to validate the information, making people deposit even more trust in this network. That said, one main goal of blockchain is to achieve transparency, making everyone in the network equal since they all have access to the same data.

Blockchain technology can also reduce certification forgeries and ensure security and validity (Madala, Jhanwar, and Chattopadhyay 2019). According to the authors, "Blockchain is the main tool to facilitate this need and when combined with different hashing techniques, this becomes a powerful method for protecting the data." (p. 1).

This can be applied in many different areas and tasks in the future that require certification to operate.

Another innovative technology that has been gaining popularity in recent years is 3D printing. As stated by Shahrubudin et al. (2019), it “is a fast-emerging technology” (p.1286), known and used in multiple areas and diverse industries, such as aviation, agriculture, health, fashion, science and more. It consists of producing three-dimensional items previously modelled in the computer. While 3D printing can be traced back to the 1980s, it has been mainly used for industrial projects and applications due to its high cost. Nowadays, they are getting more affordable and reachable, so many people are buying one to make their home items or personal objects (Sathish & Krishnan Ayyangar, 2018). Sathish and Krishnan Ayyangar (2018) stated that a 3D printer works identically to an industrial robot since it is a computer-aided manufacturing (CAM) device that helps automate a manufacturing process using software and computer-controlled equipment. The machine gets information from a PC as an input to print the model, and as it works without any help from the exterior, this process is more effective and generates less waste (Sathish and Krishnan Ayyangar 2018).

The general principle of 3D printing can be divided into three main parts: Firstly, the blueprints from the modelling software where the object is being designed are converted into digital cross-sections to act as guidelines for the printing. Secondly, when the 3D printer receives the design, it produces the object layer by layer, according to each cross-section previously created. When all the layers fuse, the print is complete. Lastly, the supports used are removed, and, in some cases, smoothing and painting can also be done (Sathish and Krishnan Ayyangar 2018). Since this technology involves fabricating objects with many different shapes and geometries through printing them layer by layer, the printing can be stopped and resumed as needed. Depending on the size of the layer where the printing occurs, the printing of several independent items can be done simultaneously and without human interference, becoming a very efficient way to manufacture the components needed, increasing production speed while keeping costs low.

Nowadays, 3D printing enables the production of various materials such as plastic, ceramic, graphene, and metal. Because of that, it has been proven feasible to reproduce complex items, such as heart pumps, jewellery, rocket engines and even a bridge built from steel. The ease with which these more complex components can be printed, makes this technology accessible to everyone. While it has great benefits, it can also have dangerous outcomes, as anyone can print threatening objects like guns and knives (Shahrubudin, Lee, and Ramlan 2019).

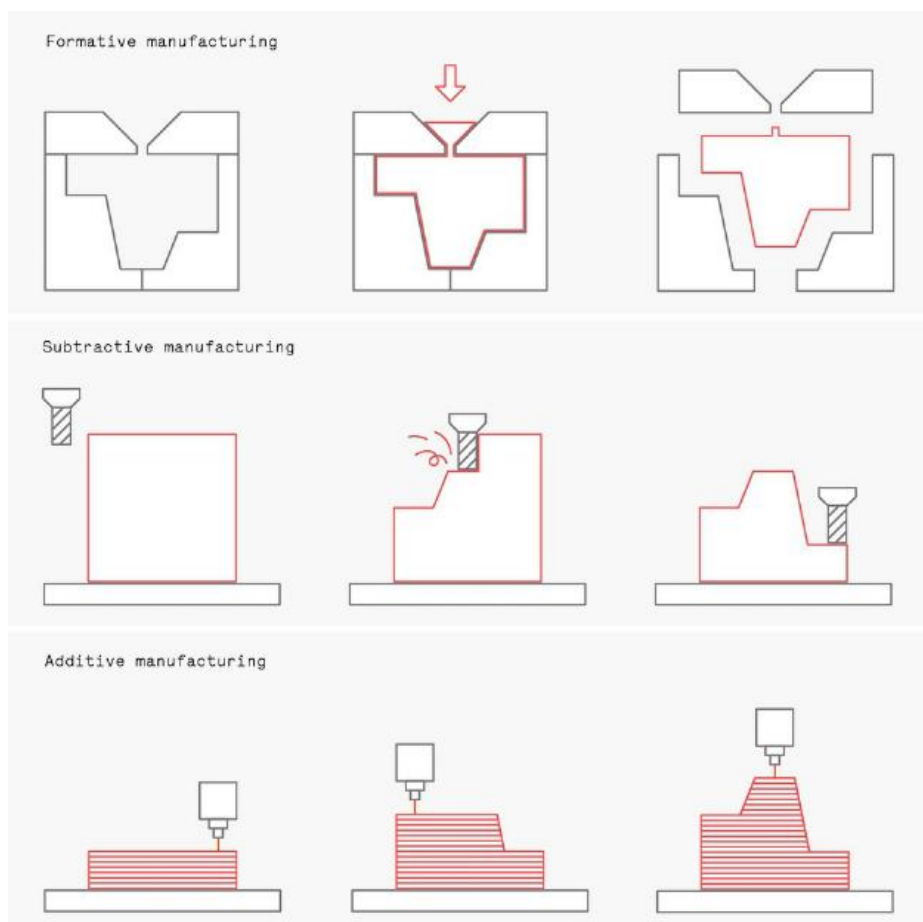
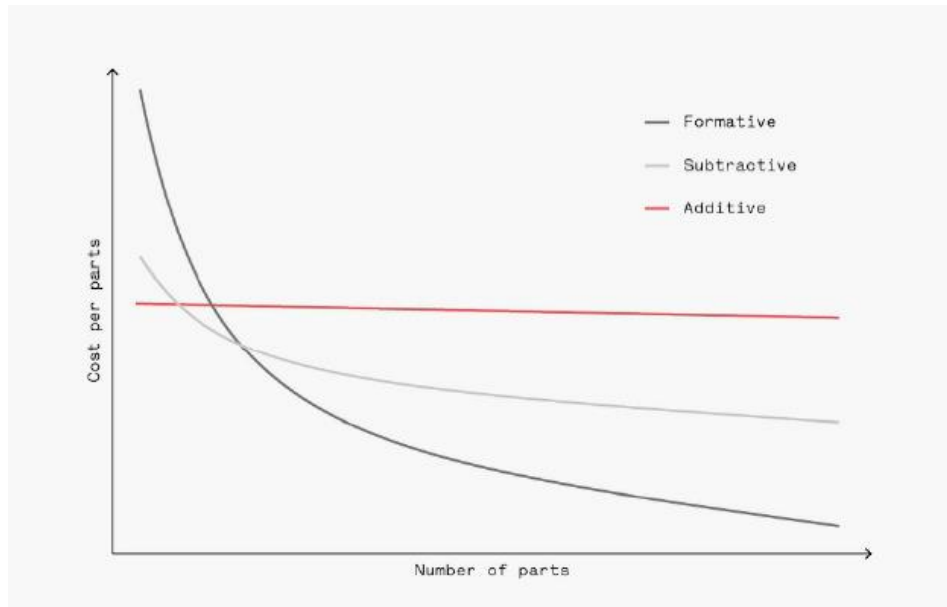


Figure 2 - Types of Manufacturing

Source: (Redwood, Schöffner, and Garret 2017)

Formative manufacturing is mostly used for high volume productions of the same model, quickly ensuring production at a low price per unit. Subtractive manufacturing is best suited for simple geometries and low-mid volume productions, usually made from

metal. Moreover, Additive manufacturing is appropriate for low volume productions and complex designs that the other types of manufacturing cannot achieve (Redwood, Schöffner, and Garret 2017). The cost of manufacturing varies accordingly to the quantity produced, as shown below in Figure 3.



**Figure 3** - Economy of scale for each manufacturing type

**Source:** (Redwood, Schöffner, and Garret 2017)

Regarding additive manufacturing methods, Shahrubudin, Lee, and Ramlan (2019) proposed seven main types: Binder jetting, Directed energy deposition, Materials extrusion, Materials jetting, Powder bed fusion, Sheet lamination and Vat photopolymerization. Depending on the target application, a different kind of manufacturing is applied. For example, if the main goal is to produce a plastic model, the designated procedure would be fused deposition modelling (FDM). In this process, the plastic is heated and put together in layers. Contrarily, the method for printing metal should be a direct metal laser sintering (DMLS) that shapes the metal's layers by using a powerful laser and metallic powder (Sathish and Krishnan Ayyangar 2018). Figure 4 describes how the five mentioned methods operate and the respective technologies used.

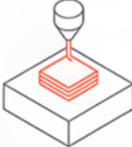





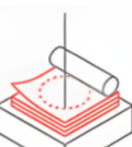
Processes	Description	Technology
	<p>Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.</p>	<p>Fused Filament Fabrication (FFF), more commonly referred to as Fused Deposition Modeling (FDM)</p>
	<p>Additive manufacturing process in which a liquid photopolymer in a vat is selectively cured by light-activated polymerization.</p>	<p>Stereolithography (SLA), Direct Light Processing (DLP)</p>
	<p>Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.</p>	<p>Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM)</p>
	<p>Additive manufacturing process in which droplets of material are selectively deposited and cured on a build plate.</p>	<p>Material Jetting (MJ), Drop On Demand (DOD)</p>
	<p>Additive manufacturing process in which a liquid bonding agent selectively binds regions of a powder bed.</p>	<p>Binder Jetting (BJ)</p>
	<p>Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.</p>	<p>Laser Engineered Net Shaping (LENS), Laser-Based Metal Deposition (LBMD)</p>
	<p>Additive manufacturing process in which sheets of material are bonded to form a part.</p>	<p>Ultrasonic Additive Manufacturing (UAM), Laminated Object Manufacturing (LOM)</p>

Figure 4 - Classification of 3D printing technologies

Source: Adapted from Redwood, Schöffner, and Garret (2017)

Digitalization in aviation is a common issue, as paper is still widely used in this business. It is the primary method of registration and can be scanned or converted into digital papers that are compliant with the physical documents. Alternatively, this

process could consist in entering that data directly into a database. Despite the aviation industry's reputation, serious cases of documentation and licences falsification are not common occurrence nowadays, but when they occur, they have a very high impact in the overall safety of the air transport. To overcome that, a blockchain solution could be implemented, assuring accountability, immutability, and traceability for all information, making the information impossible to tamper.

One of the main world regulators, EASA, already has study groups on blockchain and its applicability in aviation. According to the European regulator, "Several white papers and scientific papers on blockchain, applied to Aerospace & Defense use cases, have been published based on blockchain experimentations or consortium working groups of diverse major industry players" (EASA 2023a). Also, "These publications on blockchain, as applied to industry, make clear that decentralized IT systems meet the data management standards proposed or imposed by the organisations and regulators" (EASA 2023a). The existing EASA regulatory provisions "do not represent a barrier to the adoption of blockchain technology, but rather an opportunity for the aerospace and defense industry to leverage the benefits of this technology. By complying with these regulations, the industry can ensure the authenticity and integrity of digital certificates and signatures, which are crucial for the safety and airworthiness of aircraft" (EASA 2023a). Although in some regulatory documents the term blockchain itself may appear, it does not show up in the regulation itself. Doing so would be imposing a tool, which is not the role of the regulator. Its purpose consists in stating the criteria to be met, and then it is up to the users to decide what methods or technologies they should utilize to meet those requirements.

As mentioned in EASA's Part 21.A.307, "A part or appliance is eligible for installation in a type-certified product when it is in a condition for safe operation, marked in accordance with Subpart Q and accompanied by an authorised release certificate (EASA Form 1), certifying that the item was manufactured in conformity with approved design data" (EASA 2023b). Therefore, as stated in EASA's Part M.A.802, to prove that the part is in conformity with all current requirements, a Certificate of

Release to Service (CRS) “shall be issued at the completion of any maintenance work carried out on an aircraft component” (EASA 2022) and “The authorised release certificate identified as EASA Form 1 constitutes the component CRS”, except when such maintenance on aircraft components has been performed according to other specific rules (EASA 2022). One concern associated with this certification method is the growing presence of counterfeit certificates that are becoming increasingly credible, so a blockchain solution in which all the materials are traced, for example with a QR code, would fully solve this problem because the technician would be able to see if the certificate is valid or not. The certification of manufacturing companies is indicated in EASA’s Part M.A.603. In the aviation industry, there are many companies that manufacture and flood the market with components that have the same part number of the original but are not certified or are forgeries of those that are approved.

Aircraft continuing airworthiness record system is addressed in EASA’s Part M.A.305, where is stated which documents must be recorded for the aircraft to maintain their certificates of airworthiness. The problem emerges as paper records often suffer from deterioration, loss and falsification and digital records can also be hacked or deleted mainly because they are stored in isolated systems. Nowadays, there is no technology as good as blockchain for a use case such as this one. With this approach there is no single point of failure as this is a decentralized system, while also providing accountability for the issuer. EASA’s Part M.A.613 about component certificate of release to service guarantees that the maintenance was conducted. Once again, with paper records, it is very easy to compromise the aircraft’s operation, since the loss of a single document can cause an airplane to be grounded. Maintenance and airworthiness review records are detailed in EASA’s Part 145.A.55, mentioning that the organization shall record all details of maintenance work carried out and provide a copy of each certificate of release to service to the aircraft owner or operator. The same problem persists because every certificate is issued in paper form.

As well as in other industries, Additive Manufacturing (AM), also known as 3D printing, is growing in aviation recently. As Gisario et al. (2019) stated, it has “attracted

more attention due to heavy investment of the principal aviation companies for developing the AM industrial applications” (p.124). According to Shahrubudin, Lee, and Ramlan (2019), 3D printing can be beneficial in the aviation industry since it “has potential to make lightweight parts, improved and complex geometries, which can reduce energy requirement and resources” (p.1291). One of the main advantages of this technology is the ability to produce shapes that would be difficult or impossible to produce using traditional manufacturing methods (Gisario et al. 2019). Additionally, metal AM can lead to weight reduction in the final product, which itself can lead to improved performance, fuel efficiency and lower CO<sub>2</sub> emissions. Furthermore, it can result in cost savings and reduced lead times, this happens because the process of metal AM is more efficient and flexible compared to conventional manufacturing methods (Gisario et al. 2019). As the authors state, “the impact would be even bigger when parts have a high functional value and lead-time becomes critical for safe and ready operations” (p.130).

In the commercial aviation industry, various materials are used in metal AM, including aluminium, titanium, nickel-based alloys, and steel (Gisario et al. 2019). Titanium, also referred to as Ti-6Al-4V or Ti64, is extensively used in aviation, making this sector responsible for around 60% of its worldwide demand. Through their commercial and military applications, Boeing and Airbus account for 90% of this need (Gisario et al. 2019). This material is used for main structural components because of its characteristics such as good corrosion resistance, low density, and high strength, that ensure that the aircraft is compliant with the safety level required (Gisario et al. 2019). AM has been used to produce spare parts of components like engines, which need regular replacement since they get damaged easily. The landing gear is also an area of application that is growing in popularity. In the future, it is predicted that larger spare parts like airplane wings will be produced by AM technology (Debnath et al. 2022). For example, as Gisario et al. (2019) stated “in the Airbus A350 aircraft the engine pylons, most parts of the landing gears, some reinforced structural frames, and a great extent of brackets are done in Titanium” (p.130).

To meet the application requirements, AM-produced objects require post-processing techniques to enhance mechanical properties and surface roughness (Gisario et al. 2019). According to the authors these include techniques that enhance surface quality, such as hot isostatic pressing, which helps minimize porosity and improve the microstructure, or heat treatments for releasing residual strains resulting from thermal stress (Gisario et al. 2019). Besides that, cold rolling, laser polishing and laser shock peening are also examples of post-processing options for AM-fabricated components which affect surface roughness, residual stress, surface hardness, and other factors (Gisario et al. 2019).

The aviation industry needs higher numbers of highly valuable replacement components due to erratic and unpredictable demand (Debnath et al. 2022). As the same authors state, when preventative maintenance is performed or when any components randomly fail over the part life cycle, there is an exceptional need for spare parts. As a result, managing spare parts has become critical since components cost more to store and considerable shortage costs and obsolescence risk are unavoidable. Suppliers must make older spare parts for a limited life cycle, which presents an unknown barrier to their business investments (Debnath et al. 2022). High stock levels may be a solution to this problem, but they can also raise the risk of obsolescence cost, holding costs, and cash flow constraints (Debnath et al. 2022). Additionally, a lack of availability of spare parts may result in a lack of dependability, a delayed response time, and a poor cycle service level (CSL), all of which contribute to poor supply chain performance (Debnath et al. 2022).

The current state of the aerospace spare parts industry includes challenges such as long lead times, low flexibility, and the difficulty of obtaining spare parts for older aircraft (Debnath et al. 2022). AM is very likely to revolution spare parts' manufacturing and distribution process since it can offer customisation with many details with a lower cost and energy consumption (Gisario et al. 2019). Also, when compared to conventional manufacturing procedures, AM production line sustainability increases in a highly noticeable way, which has a positive impact on the environment (Debnath et al. 2022).

Using AM in the aviation industry provides another advantage: improving the Buy-to-fly (BTF) ratio, which compares the amount of raw material required to produce a specific part with the mass of the final product Gisario et al. (2019). “Currently, by using the Conventional Manufacturing (CM) processes, the BTF ratio for aircraft components is in the range of 12:1 – 25:1 and results in very poor material efficiency” (p.124). Since titanium is more expensive than substitute metals like stainless steel or aluminium and because it is difficult to machine using conventional technologies, the parts with high BTF ratio would be excellent candidates for production using technologies like AM (Gisario et al. 2019).

3D printing is also valuable for producing non-critical objects that are already out-of-production. Lim et al. (2016) noted that “Airbus recently printed a small plastic crew seat panel used in Canada’s Air Transat A310, as the part is no longer in production” (p.20). The same authors stated that, according to Airbus, the use of AM could reduce airliners’ costs by 10 to 30% in the long term. Inventory management, which is a difficult task for many aircraft companies, can also be aided by AM (Togwe, Eveleigh, and Tanju 2019). As the same authors conclude, when the forecast for a traditionally manufactured spare component is lower than the actual need, AM could be utilized to fill the gap, thus reducing the risk of spare part shortages. Also, producing spare parts on demand reduces the inventory holding costs and increases the spare parts availability (Togwe, Eveleigh, and Tanju 2019).

The supply chain for AM can be either centralized or decentralized (Debnath et al. 2022). For overall costs in the aerospace spare parts industry, a centralized scenario is now recommended over a decentralized one, although the latter improves customer response while lowering costs and reducing both lead and transportation times, since the product is manufactured close to the consumer (Debnath et al. 2022). Additionally, it has fewer carbon emissions than a centralised supply chain since production emissions are lower and there is less outward transit (Debnath et al. 2022). Centralised additive manufacturing (AM) is currently more cost-effective compared to decentralised AM. However, there is a prediction that decentralized AM will become less expensive in the future, due to advances in automation, reduced prices and small-sized machines

(Debnath et al. 2022). As stated by the same authors, one great advantage of a production system that uses decentralised manufacturing, such as cyber-physical systems automation with enhanced quality, is the ability to respond to unpredictable demand.

While metal AM holds great potential for revolutionizing the commercial aviation industry, further research, development and standardization are needed (Gisario et al. 2019). According to the authors, there is still another significant limitation of using metal AM in the commercial aviation industry, as the high cost of equipment and materials is a barrier for small and medium-sized companies to adopt this technology, although these costs are expected to decrease as it becomes more widespread. Additionally, the lack of standardization in the industry can make it difficult for companies to adopt metal AM, as there are currently no widely accepted standards for the quality control and certification of metal AM parts. AM must be able to continuously achieve the same results in an industrial setting to be widely adopted in a sector with such stringent regulations as the aerospace one (Gisario et al. 2019). Moreover, it must be possible to produce the same results on geometries that could appear quite different, possibly on different machines, and using feedstock from various suppliers (Gisario et al. 2019). The same authors emphasize that the future success of this innovative field in the industry relies on advancing AM technologies and methods, developing new materials, and even upgrading the existing manufacturing systems.

Although there are many applications for blockchain technology in the aviation sector, its full potential has not yet been properly developed (Li et al. 2021). Some advantages of using blockchain in the aviation industry include payment, identity management, customs clearance, air traffic control and tracking (Li et al. 2021). Examples of those applications are presented in Figure 5. With the advent of smart contracts, it's now possible to create decentralized applications that don't require a trusted third-party (Khan et al. 2021). As stated by Khan et al. (2021), smart contracts are "computer protocols designed to facilitate, verify, and enforce automatically the negotiation and agreement among multiple untrustworthy parties" (p.1). The digital

programs are stored on a blockchain and are executed when conditions are met, automating a workflow by triggering the next action. This enables users to be immediately certain of the outcome, without any intermediary's involvement or time loss (Khan et al. 2021).

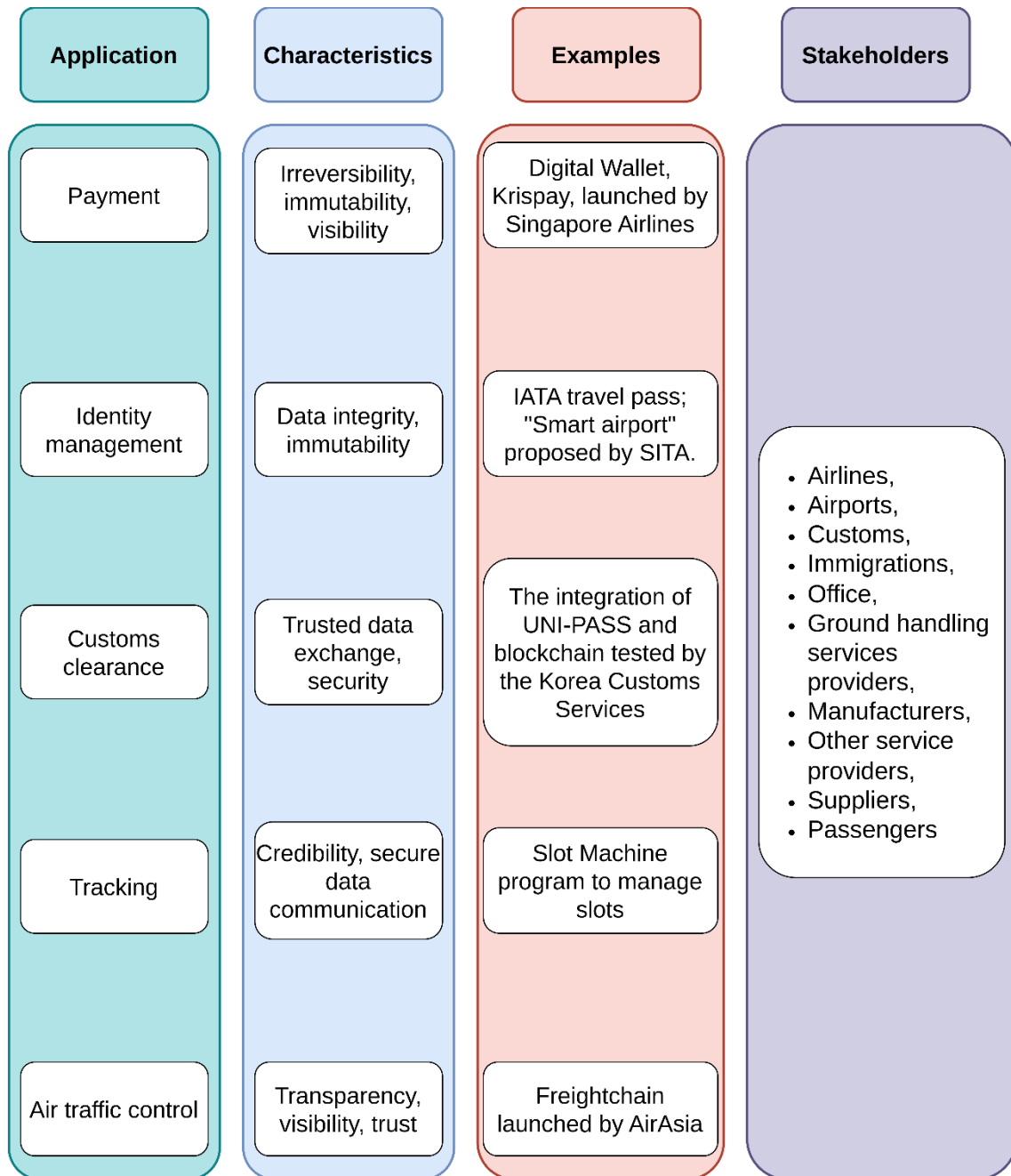


Figure 5 - Examples of blockchain applications in the aviation industry

Source: Adapted from Li et al. (2021)

According to Li et al. (2021), "IATA estimated that air passengers would increase to more than 8 billion by 2036, and airports would have to deal with more than 9 billion baggage items per year" (p.3). Since baggage loss is an important issue occurring every now and then at the airports, blockchain would help solving it by accurately trace the real time position of the luggage during every phase of that process (Li et al. 2021). This technology would give handlers better control over bags and cargo and improve its efficiency (Li et al. 2021). With the use of an unalterable record of lost baggage, smart contracts can be implemented to help insurance companies provide compensation to customers for lost or damaged baggage in a more reliable, efficient, and trustworthy manner (Ahmad et al. 2021).

To digitalize cargo shipment, blockchain technology can track items by registering monitoring sensors, carriers, and shippers onto a blockchain platform (Ahmad et al. 2021). The sensors gather data such as the cargo's location and send this information to a server to be recorded on the ledger for enhanced transparency. The technology can also record the temperature, humidity, and condition of the items within the shipping package for safety purposes (Ahmad et al. 2021). According to the same authors, for small containers transported by air, the intelligent sensors are utilized to detect and record any changes made to the items inside on the blockchain ledger. It can also detect, alert, and record any unauthorized access attempts to open the container and replace valuable assets. Some containers may hold perishable goods such as food or medicine, that require special attention, as sudden increases in humidity levels can harm the contents. In these situations, smart contracts can initiate notifications to the designated authorities, who can take the necessary steps to safeguard the items (Ahmad et al. 2021).

The customer loyalty program, also known as frequent flyer miles, rewards frequent flyers for using airline services. The current management systems face challenges such as low redemption rate, high maintenance costs, data theft, and they usually tend to benefit the businesses more than the customers (Ahmad et al. 2021). Blockchain technology is believed to improve the loyalty program by tokenizing reward points,

making them immediately redeemable when a certain amount is reached (Ahmad et al. 2021). This technology also ensures that no one, including airlines or third parties, can modify the redemption rules or tokens earned by the customers; all transactions are recorded and traced, ensuring transparency, visibility, and traceability of every earned loyalty point (Ahmad et al. 2021). Tokens on the blockchain system cannot expire, unlike traditional reward systems and smart contracts can also help airlines allocate, redeem, and share revenue from loyalty points in a cost-effective and compliant manner (Ahmad et al. 2021).

Another domain where blockchain can be applied in the aviation industry is in ensuring the competency of aircrews, as it is crucial for safety and environmental protection (Ahmad et al. 2021). Crew certificates are issued to pilots to confirm their required knowledge and experience, but the lack of trustworthy verification can pose dangers. The aviation industry typically employs manual or centralized data management systems that are prone to error and fraud (Ahmad et al. 2021). Blockchain technology can help digitize aircrew certificates to verify the claimed skills in real-time and improve trust among aviation industry stakeholders. Crew certification can be authenticated to eliminate the chances of fake certificates, while access to pilot skills and experience data can boost passenger confidence (Ahmad et al. 2021). However, according to the same authors, implementing this process is complex and requires the cooperation of multiple organizations, including flight schools and aviation authorities. This process can also be extrapolated to all the certifications and training in the aviation ecosystem. Aircraft maintenance technicians and engineers must have certifications and training, like the ones from the flight crew. As soon as the process is available for the flight crew, can be easily extrapolated for the maintenance technicians and engineers, cabin crew, air traffic controllers, just for stating a few.

Blockchain technology can also be used to create a transparent and trustworthy view of an aircraft's historical data and maintenance records. This can help stakeholders, such as the FAA and buyers, verify an aircraft's airworthiness and health score (Ahmad et al. 2021). This technology enables the registration of all aircraft components and spare

parts, providing MRO service providers with a timestamped and traceable record of their operational history and provenance. The MRO service provider can use blockchain-based maintenance logbooks to record the repair history, estimate the competency of components, and automate the scheduling of maintenance services (Ahmad et al. 2021). This would contribute to aviation safety by reducing corruption, since counterfeit products cannot be validated by this technology (Li et al. 2021).

Generally, in aviation, many documents are required for multiple purposes. Therefore, blockchain can also be useful for document handling, by reducing the paperwork while sharing reliable and real-time information between every part involved (Li et al. 2021). According to Li et al. (2021), this DLT will also help smart airports implement a digital identity management system, such as SITA's e-passport, in which passengers are automatically identified and their biometric data is securely kept or an e-commerce platform using digital wallets. In air traffic management, blockchain could contribute for the creation of a decentralized air traffic platform, as well as a system that addresses its problems. This would increase information security and prevent disruptions when the airport systems are attacked, since they are all centralised (Li et al. 2021). As these authors claim, multiple entities are already designing, proposing, and testing blockchain systems to secure air traffic communications and its privacy.

According to the main mission and vision of the airport industry, blockchain technology significantly influences the overall services provided in the airport by making them more satisfying and highly standardised, adhering to passengers' collective attitudes and needs (di Vaio and Varriale 2020). The same authors state that the airport supply chain has many applications for blockchain technology, including maintenance, passenger and crew identity management, ticketing, loyalty, security, ancillary revenue and in-flight entertainment, luggage chain of custody, air cargo, customs clearing, flight planning, smart contracts, and compensation.

Blockchain technology can provide secure identity management for the aviation industry by only allowing entities to access certain services after successful authentication checks (Ahmad et al. 2021). It can also tokenize traditional ticketing

systems, ensuring that ticket sales and purchases are immutable and traceable on the blockchain. This reduces the chances of ticket fraud and duplicate sales, which can improve the passenger experience (Ahmad et al. 2021). Smart contracts on the blockchain can automate the ticket transferring process for airline alliances and facilitate timely cash refunds if passengers cancel their purchased tickets. Furthermore, the use of smart contracts can quickly notify passengers about cancelled flights and transfer the reimbursed amount to their wallets, making the process more efficient (Ahmad et al. 2021).

Airport collaborative decision making (A-CDM) is a critical component of supply chain management (SCM) effectiveness and efficiency (di Vaio and Varriale 2020). A-CDM is another AI based system that proposes real-time operational information exchanges with the air traffic management office, so that the decision-making process could be improved (di Vaio and Varriale 2020). Due to its improved predictability, A-CDM could help reducing the buffer times for resource planning and flight times. Airports may automate as much as possible to increase the formation flow and provide digitised services thanks to the latest technologies in blockchain applications and A-CDM. Having more information on the airport system would provide value and enable simpler information distribution to passengers, airlines, staff, and other users. Additionally, the airport could get more information from passengers and other partners (di Vaio and Varriale 2020). With the significant increase in commercial aircraft, airport congestion has become a pressing issue (Ahmad et al. 2021). To minimize service delays, ACDM works to efficiently utilize available airport resources, where transparency is crucial, and shared information must be accessible to all stakeholders in the aviation industry, including ground handlers, air traffic controllers, and airport operators (Ahmad et al. 2021).

The Napoli-Capodichino airport has adopted the A-CDM system to address major inefficiencies in its management and optimize its infrastructure by utilizing all available data. The limited visibility of the flight processes and operations that involve multiple airports affects the planning and, ultimately, the sustainability of the performance (di Vaio and Varriale 2020). The A-CDM project represents a shift in the "turnaround"

management approach from "first come, first served" to "first ready, first served". It is a comprehensive platform that transmits real-time information on the status of all departing flights to the EUROCONTROL Management Operations Centre, which then distributes this information to partner airports. By doing so, the system optimizes air traffic flow, airport capacity management, and resource utilization, resulting in improved punctuality, reduced fuel consumption and its associated environmental impact. It also increases airport efficiency, timeliness, and can aid event predictability. The digitalization of operations and standardized communication among stakeholders reduces the potential for errors. The program, based on an information exchange platform, considers all flight phases, from departure to landing, as a "single process," ensuring optimal air traffic management and ground handling operations (di Vaio and Varriale 2020).

The benefits of A-CDM, made possible through the sharing and prediction of aircraft available times, enable the airport to plan earlier departure sequences, improve runway and taxiway management, and decrease fuel consumption by reducing aircraft holding times. This results in more time to resolve gate conflicts and enhances the passenger experience, while ground handlers can more efficiently allocate their resources (di Vaio and Varriale 2020).

As Figure 6 shows, without A-CDM aircrafts are handled according to the first come – first served principle. They receive clearance in the same order, making them depart outside the slot tolerance window. Waiting time at the runway increases, which results in higher fuel consumption and, consequently, higher polluting emissions (di Vaio and Varriale 2020). On the other hand, with A-CDM aircrafts are handled based on the best planned – best served principle. Their clearance order is based on numerous factors such as variable taxi time, de-icing time, runway waiting time, etc. This will enable the best possible sequence for the aircrafts to be cleared to the runway in due time, reducing the waiting time and improving slot adherence (di Vaio and Varriale 2020). The charging system for aircraft maintenance services has traditionally been based on the time the aircraft spends at the airport gate. However, the transparency provided by

### 3D Printing with Blockchain Released Certificates in the Aviation Industry

blockchain technology can enable airlines to trust a pay-as-you-use billing model. Additionally, blockchain can be used to verify and audit ground handlers' actions during baggage loading and unloading processes (di Vaio and Varriale 2020).

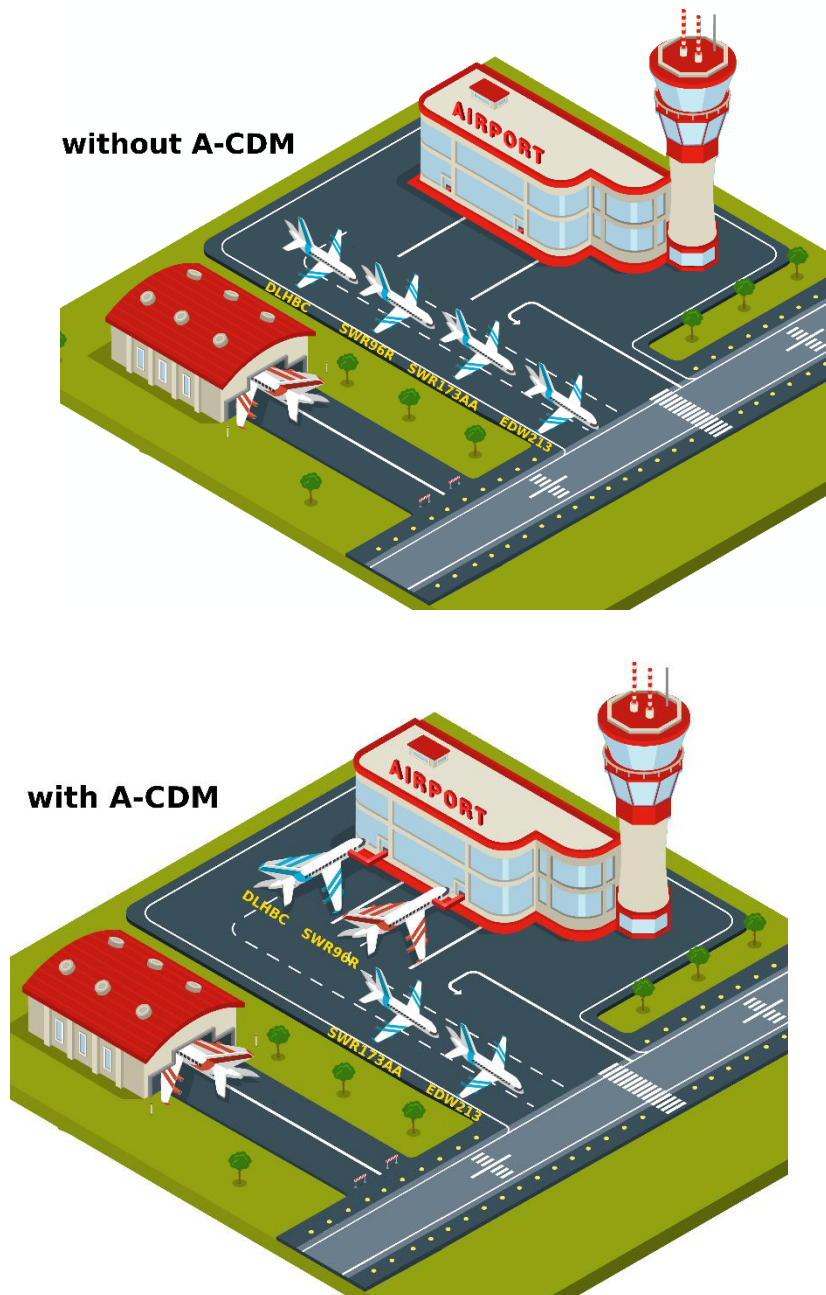


Figure 6 - A-CDM Management

Source: Adapted from (di Vaio and Varriale 2020)

Another company that illustrates the usage of Blockchain in the aviation industry is Earhart Solution. As stated by Earhart (2020), the Portuguese organization proposes “a blockchain modular powered solution, that engulf most of the aviation ecosystem under the same ledger, and which has the potential to transform how the trustworthiness and traceability of aeronautical records is stored and used” (p.3). By using blockchain technology, every record will be forever stored and immutable, which would solve the paper and nonstandard aviation records issue. Since the data may be accessed in real time, many aspects of the daily management of aircraft will be simplified, such as in operations, training, manufacturing, and maintenance (Earhart 2020).

One of the main risks of 3D printing applications in the aviation sector that may be addressed with blockchain technology is the possibility of malicious data manipulation, especially when sensitive data is transferred between organizations (Klößner et al. 2020). For example, an aircraft OEM sending a design file to a maintenance provider for printing could result in IP management issues or design tampering during the transfer (Klößner et al. 2020). According to the same authors, an example of the severity of this threat is the manipulation of a hacked drone CAD file which caused the drone to crash shortly after takeoff. 3D printing offers certain risks and makes the whole supply chain more distributed, which may involve passing on sensitive data to people who are not fully trusted (Klößner et al. 2020). To prevent threats to IP and data, the 3D printing value chain needs efficient security measures, so blockchain technology can be used to provide that and safeguard data records against tampering (Klößner et al. 2020). Blockchain can help make 3D printing safer by serving as an underlying safeguarding layer (Klößner et al. 2020).

The combination of blockchain and 3D printing could be a revolutionary solution for a wide range of industries including aviation, by linking the two into a value chain platform as shown in Figure 7. The digital nature of 3D printing makes it easier to incorporate blockchain technology since the 3D printing process is already largely digital, so connecting it to a digital ledger like blockchain is both practical and feasible (Klößner

et al. 2020). These technologies' emergence also allows the creation of new business models, which can vary from the creation of local 3D printing, secured shared factories, and design marketplaces (Klößner et al. 2020).

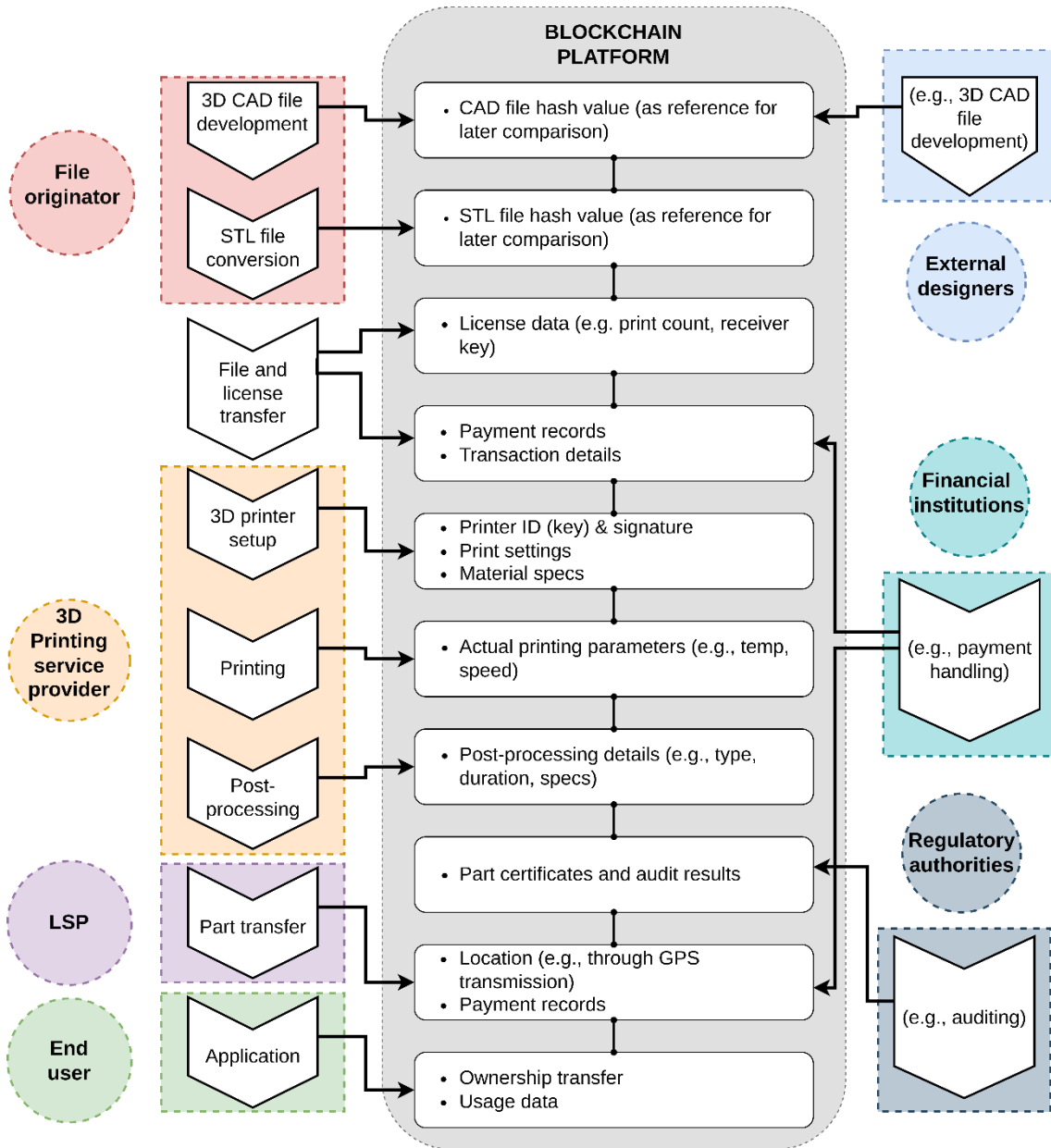


Figure 7 - Blockchain platform for 3D printing

Source: Adapted from Klößner et al. (2020)

The combination of blockchain and 3D printing has proven beneficial for aviation companies, allowing them to print aircraft components as needed and reducing

inventory and logistics costs (Attaran & Gunasekaran, 2019). As the authors state, “Blockchain securely transfers the data to a verified 3D printer, enables authentication of the part, and helps technicians ensure that it was not counterfeit before the installation into an aircraft” (p.436). One illustrative example of that is VeriPart, a blockchain-based service that verifies instructions for 3D printed components and guarantee their authenticity (Lacity 2018). As said by the same author, “Once a part has been printed, VeriPart will trace it through the supply chain until it is decommissioned” (p.209). The platform was created by Moog, a U.S industrial manufacturer and provider of integrated control systems for aircraft (Lacity 2018). Moog plans to use VeriPart, a platform that integrates 3D printing, blockchain, and AI technologies, to manage the entire lifecycle of 3D printed parts. The company believes that a blockchain solution is necessary to ensure security and resiliency and to avoid reliance on a single trusted third party to control the service (Lacity 2018). To maintain the integrity of the parts in the supply chain, the manufacturer designed a two-layer authentication protocol. The first layer involves printing each part with a unique embedded hash "watermark," which can be viewed using a smartphone app. The second layer involves permanently storing the hash on the blockchain at the time of origin. The blockchain application will track each movement and transfer of ownership of the part, enabling it to be traced through the entire supply chain (Lacity 2018).

Air New Zealand has already tested VeriPart, by ordering a replacement for one protective part of a Boeing 777-300 Business Premier seat screen, when it was flying from Auckland to Los Angeles (Shah 2019). Through that system, the maintenance team in New Zealand ordered a digital design file of the specific part, so that it could be printed in Los Angeles and installed in the airplane as soon as it landed. By solving the problem, they prevented the loss of revenue that the loose use of the seat on the return leg would provoke, as well as the amount of time that they needed to wait until the suppliers could finally replace the damaged part.

### **3D Printing with Blockchain Released Certificates in the Aviation Industry**

As the benefits of blockchain and 3D printing in aviation become increasingly evident, major aviation corporations are expected to launch and develop pilot breakthrough projects to expand the use of these technologies on a larger scale.



### CHAPTER III- STUDY DESIGN

In the previous chapter, an extensive literature review was conducted on the integration of blockchain and 3D printing technologies in the aviation industry. This review encompassed a wide range of studies exploring the potential applications and benefits of combining these technologies. Building upon the insights and research gaps identified in the literature, this chapter presents the design of the study proposed, by understanding the aircraft supply chain first and then propose an innovative approach to it.

Every industrial sector needs a strong supply chain management system in order to thrive. To reach a final product, a series of different specialized manufacturers produce, individually, their parts. Subsequently, they go through a multi-tier supply chain that allows them to reach their destination (Madhwal and Panfilov 2017). This is especially true in the aviation industry, where a proper inventory is kept, individual components of an aircraft's body are acquired, and the final product is assembled domestically (Madhwal and Panfilov 2017).

The aircraft supply chain structure is mainly composed by three parties: sellers, service providers and customers. OEMs (Original Equipment Manufacturers) are the sellers; they oversee the conception, creation, and assembly of the large components, as well as the testing and delivery of the finished product to the customers. Examples of OEMs are Boeing and Airbus (Ghadge et al. 2018). On the other hand, MROs (Maintenance Repair and Overhaul) ensure the aircrafts' airworthiness during the periodic inspections (Singamneni et al. 2019). They are in charge of keeping or restoring aircraft parts to a condition that will allow them to carry out their intended design functions. MRO activities primarily involve servicing, repairing, altering, overhauling, inspecting, and assessing the condition of the aircraft, particularly during routine periodic inspections (Singamneni et al. 2019).

The main responsibility of this aviation sector can be summed up as being primarily in charge of providing an operator with an aircraft that is fully serviceable at a

reasonable cost, and of the highest possible quality (Ayeni, Ball, and Baines 2016). Depending on the type of network, MRO companies sign contractual agreements with either airlines or OEMs (Ghadge et al. 2018). MROs do not operate on their own, as the service they provide depends on the OEM for part’s supply (Ghadge et al. 2018).

There are many levels of assembly that go into creating a single finished product, however some studies have grouped these levels into three main supply tiers (Madhwal and Panfilov 2017). Figure 8 illustrates the multi-tier supply chain, showcasing the direct relation between first-tier suppliers and OEMs. First-tier suppliers are responsible for manufacturing and assembling major aircraft components such as engines and landing gears. To do so, they also buy raw materials or manufacturing products from their supplier base (Ghadge et al. 2018). Second-tier suppliers often supply their first-tier counterparts: they can either provide in-house made products or resort to a variety of other external providers. Lastly, third-tier suppliers provide small and specific components (Madhwal and Panfilov 2017).

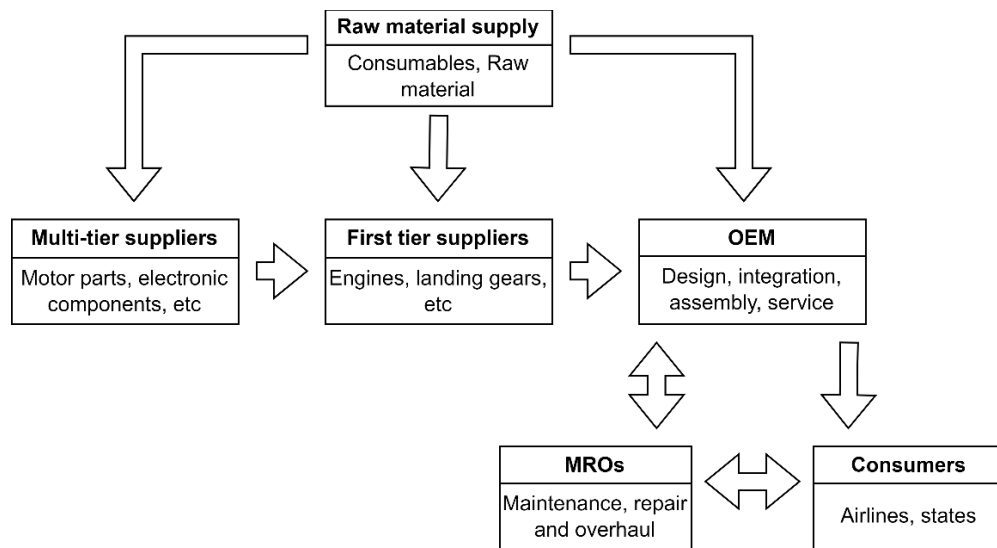


Figure 8 - Aircraft supply chain structure

Source: Adapted from Ghadge et al. (2018)

The aircraft supply chain is composed by all the processes and businesses that make it possible to produce parts in time to meet supply with demand (Ghadge et al. 2018). OEMs together with MROs allow the consumers (airlines) to maintain their fleet operational and adequately supplied. The efficiency of these chains relies heavily on both external factors such as transportation methods, as well as internal factors such as the availability of inventories to meet demand (Madhwal and Panfilov 2017). According to the authors, these chains involve “vast quantities of exorbitant amount of flow information, product and money” (p. 1054).

Aircraft MRO organizations must be approved by aviation authorities. They are responsible for carrying out scheduled or unscheduled maintenance events that involve the replacement of spare parts in aircraft (Singamneni et al. 2019). End users, such as airline operators, usually outsource maintenance services to MRO organizations so they can focus on their core tasks. MRO activities make up a significant portion of the aerospace industry's revenue, with selling spare parts often generating more profits than selling original equipment (Singamneni et al. 2019). Aircraft components consist of many parts that need high-standard inspections, but demand is usually unpredictable, which can stretch inventory levels to their limits. Regular replacement is only needed for around 10% of the spare parts, while the remaining parts, referred to as "slow-moving parts" or "Long-Term Storage parts," are hard to predict the exchange times and become expensive (Singamneni et al. 2019).

Spare parts are classified into four types: Rotatable, Repairable, Expendable, and Consumable, each with a different replenishment policy. Inventory analysts are responsible for assigning specific policies to hundreds and thousands of spare parts, which are associated with the volume of the repair and the supply lead times and need to be updated regularly to adapt to market changes (Singamneni et al. 2019). Predicting spare parts demand is challenging, and at times a spare part might not be in production anymore, making aftermarket service difficult and leading to inefficiencies in the supply chain systems of the aircraft operations industry. High inventory levels can reduce aircraft downtime, but the total financial investment becomes astronomically high.

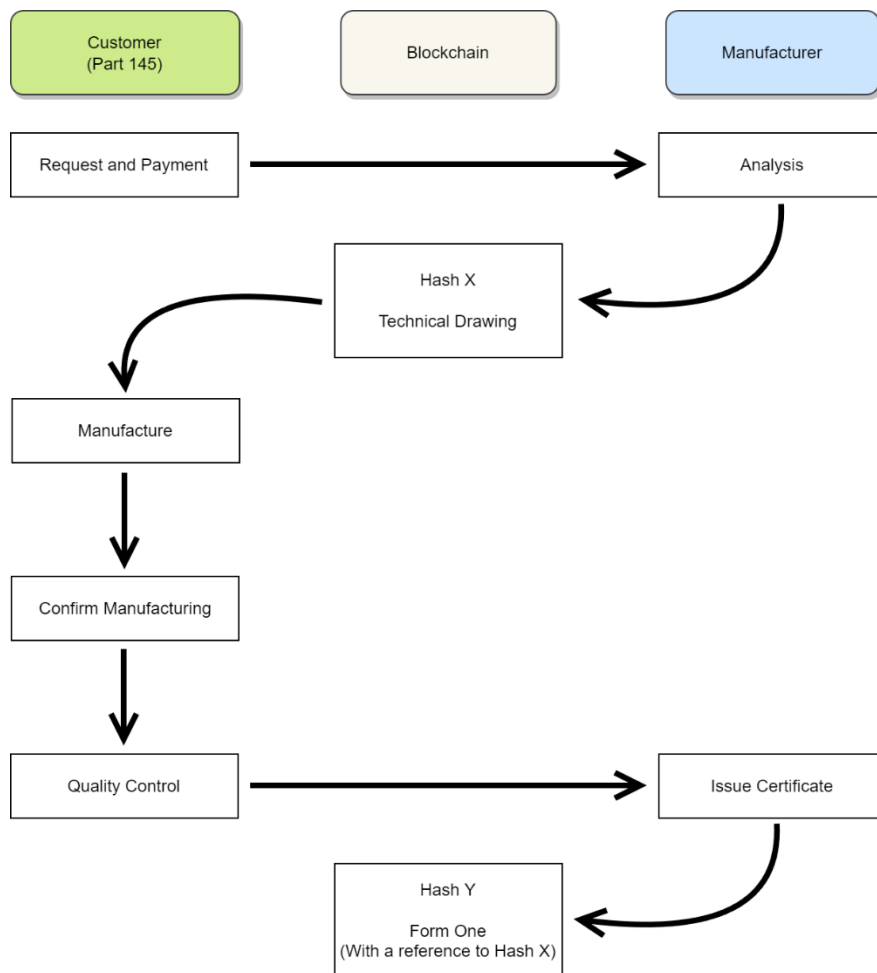
Therefore, customers use several strategies in the material service value chain, such as insourcing or outsourcing, and contractual agreements with different suppliers, MROs, and other distributors, so that they share the inventory pressure from both suppliers and buyers (Singamneni et al. 2019).

Commonly, airline operators have their own maintenance teams and warehouse operations in place, where they keep a supply of frequently replaced spare parts. Meanwhile, customers either keep a small inventory of infrequently replaced parts or purchase them from nearby MRO companies, manufacturers or distributors (Singamneni et al. 2019). According to the same authors, the aircraft industry's inventory costs worldwide are estimated to be around USD 50 billion. To reduce stock levels, the industry has implemented various strategies such as forecasting parts demand, predicting maintenance needs using algorithms, and optimizing supply chain configurations. However, these measures have been only moderately effective due to high transaction costs and delayed aircraft servicing.

Modifications to security systems, fuel consumption, policy changes, and technology innovations also cause design alterations, leading to manufacturing complexities, supply chain problems, and, consequently, increased costs (Singamneni et al. 2019). Customization in the cabin is an example of a major competitive factor for passenger airlines, but they often delay making detailed specifications until 6 to 12 months before delivery due to financial constraints and varying business models. The high level of customization and less-frequently-used parts also make it challenging to provide timely production and maintenance services while maintaining good profits. The industry also faces supply chain risks related to competition for resources such as titanium and aluminium alloys, carbon fibbers, and their composites. The traditional manufacturing methods used in the industry are also inefficient and wasteful, making it necessary to explore more advanced and alternative methods of manufacturing, such as additive manufacturing (Singamneni et al. 2019).

Manufacturers have been trying to optimize design and production processes by using lean manufacturing approaches, advanced automation, computer-aided design,

and manufacturing to reduce waste and production lead times and improve products and services (Singamneni et al. 2019). For that matter, considering this challenging reality, an innovative approach is proposed, enhancing the development of additive manufacturing and blockchain. Figure 9 represents the solution of adding blockchain technology as an intermediate between the customer and the manufacturer, which allows them to certificate the components produced and maintain them traceable and accessible for every part along the way.



**Figure 9** - Proposal for a Blockchain-based solution for 3D printing in the aviation industry

**Source:** Elaborated by the author

First, whenever a customer (Part 145 Maintenance Organization) needs a spare part, he would request it and pay the manufacturer. After its analysis, the manufacturer would create a block in a blockchain. This block would contain a unique identifying hash, as well as a technical drawing of the requested part, so that the customer can 3D print it. Subsequently, the component would go through quality control to ensure that the printed part is compliant with manufacturer standards. After this evaluation, the manufacturer would issue the part certificate (EASA Form 1) and then add it to a newly created block within the blockchain. This block would also contain a specific unique hash, as well as a reference to the block containing the part's technical drawing, so that security and fidelity of data are assured. This way, both parts can access and trace the component throughout its process of manufacturing until delivery. Additionally, the customer can have access to a detailed record of the component's entire journey, including its origin, manufacturing date, and all the tests it went through, which helps with maintenance and repairs in the future. By using the blockchain technology, the entire process becomes more transparent, secure, and efficient.

Implementing a project like the one proposed involve both direct and indirect costs. The direct costs associated with the implementation of a blockchain infrastructure system comprise development costs, testing and validation costs, equipment costs, labour costs, operational costs, regulatory and compliance costs, and opportunity costs. Development costs refer to expenses related to the creation of the blockchain solution and the development of software and hardware, while testing and validation costs encompass expenses linked to the testing and validation of the system to guarantee its reliability, security, and compliance with industry standards and regulations. Moreover, equipment costs refer to the expenses incurred in purchasing or upgrading the equipment required for 3D printing and quality control. Labour costs comprise the expenses involved in hiring personnel and training, while operational costs refer to expenses related with software updates and bug fixes. Lastly, regulatory compliance costs comprise expenses related with certification.

There are also several indirect costs associated with implementing a project such as this. Developing this solution may require resources and attention that could otherwise be allocated elsewhere within the organization, impacting other projects thus leading to opportunity costs. These costs are difficult to quantify as different organizations will have different structures, leading to unpredictable expenses. Being a long-term solution, it is also important to consider the inflation rate in a project of this size.

Adding blockchain technology in the aviation supply chain would bring various potential benefits, such as improved transparency, enhanced security, increased efficiency, better customer service and cost savings. First, the use of blockchain technology in this project enables a more transparent and visible record of the component's journey from manufacturing to delivery. The unique identifying hash and reference to the technical drawing in each block provide an additional layer of security and help prevent counterfeiting and fraud. By increasing transparency, customers can trust that the component they are receiving is genuine and has undergone proper quality control checks. Furthermore, blockchain technology provides an immutable and tamper-proof record of each component's journey. Each block in the blockchain contains a specific unique hash and a reference to the technical drawing, ensuring the security and fidelity of data. By implementing this project, costs can be saved, and the reputation of the manufacturers are secured.

On the other hand, the use of 3D printing technology enables customers to print the component themselves, reducing the time and costs associated with traditional manufacturing and shipping. This also helps to reduce lead times and increase the speed of delivery. By leveraging this technology, the manufacturing process becomes more efficient and cost-effective, which can help manufacturers remain competitive and offer more value to their customers. 3D printing can improve component quality and accuracy, especially for complex or customized components and, by using blockchain technology to track and verify component quality throughout the supply chain, manufacturers can ensure that all components meet the required specifications and

standards. Additionally, they can more easily comply with regulatory requirements in both civil and military aviation, consequently improving regulatory compliance. Sustainability would also be improved in a way that 3D printing can help reduce the waste of materials and energy during production.

The detailed record of each component's entire journey, including its origin, manufacturing date, and all the tests it went through, can help future maintenance and repairs. This provides a better understanding of the component's history, ensuring that it is repaired or maintained correctly. Besides, customer satisfaction and trust can be improved, leading to more repeat business and a stronger reputation in the market.

In order to quantify the costs of the project, these can be divided into two groups: the costs related with the development of the blockchain structure and the costs regarding 3D printing technology. As stated in “Capitalization of Software Development Costs — AccountingTools” (2023), capitalizing the costs related with the development of internal-use software include hardware installation, software purchase, testing, and expenses related with personnel, namely the remuneration and training. Furthermore, according to “A Cost Perspective on 3D Printing | PwC Belgium” (2018), the direct costs related to 3D printing involve machine, material, and labour, this last including post-processing activities such as quality checks. Based on this, the annual costs of the project as developing the blockchain solution can be determined by equation (1).

$$C_d(x) = p_{IT}r_{IT} + h + s + p_T r_T + ne + xf + q_e + p_{HR}r_{HR} + t + u + c \quad (1)$$

$C_d$  as a function of  $x$  represents the annual cost of the project considering the in-house development of the blockchain solution.  $x$  is the number of 3D printed parts per year,  $p_{IT}$  is the number of Information Technology (IT) employees,  $r_{IT}$  is the annual salary of one IT employee,  $h$  is the annual hardware expenses,  $s$  is the annual software expenses,  $p_T$  is the number of tester employees,  $r_T$  is the annual salary of one tester employee,  $n$  is the number of 3D printers required for the project,  $e$  is the price of one 3D printer,  $f$  is the price of one carbon fibre filament spool,  $q_e$  is the price of quality

control equipment,  $p_{HR}$  is the number of Human Resources (HR) employees,  $r_{HR}$  is the annual salary of one HR employee,  $t$  is the annual training expenses,  $u$  is the annual expenses on software updates and bug fixes, and  $c$  is the annual certification expenses.

Alternatively, to quantify the cost of the project as contracting the blockchain solution, the expenses related with software development in equation (1) should be replaced by the actual cost of contracting it. This way, the annual costs of the project in these conditions can be determined by equation (2).

$$C_c(x) = b + ne + xf + q_e + p_{HR}r_{HR} + t + c \quad (2)$$

$C_c$  as a function of  $x$  represents the annual cost of the project considering an external company is hired to develop the solution.  $x$  is the number of 3D printed parts per year,  $b$  is the annual cost of hiring a blockchain development company,  $n$  is the number of 3D printers required for the project,  $e$  is the price of one 3D printer,  $f$  is the price of one carbon fibre filament spool,  $q_e$  is the annual cost of quality control equipment,  $t$  represents the annual training expenses, and  $c$  the annual certification expenses.

By implementing a project such as the one being described, some costs related to the traditional supply chain method will no longer be applicable. This way, the annual gains of the project can be quantified by adding the costs related with warehouse (personnel, stocking), supply chain (transporting), operational (cost of selling one seat), data security and price difference between the original part and the printed one. These gains can be determined by equation (3).

$$G(x) = p_L r_L + nax + xg + xt + (1 - 0,95f)x + fx \quad (3)$$

$G$  as a function of  $x$  represents the annual gains compared with the traditional way of acquiring the parts.  $x$  is the number of 3D printed parts per year,  $p_L$  is the number of warehouse employees,  $r_L$  is the annual salary of one warehouse employee,  $n$  is the annual number of seats not sold due to broken parts,  $a$  is the annual revenue by seat,  $g$

is the cost of storing one spare part, and  $t$  is the supply chain cost of one spare part. When comparing 3D printing with traditional manufacturing methods, the cost of the 3D printed part is much lower. This happens because with 3D printing the only direct costs are the material cost and the energy cost of producing the parts, this last being negligible since cabin parts are relatively smaller and faster to print. With that being said, the assumption was made that a 3D printed part would cost 95% less than the original one, with  $f$  representing the cost of the original spare part.

Besides these quantifiable gains, there are also other gains difficult to estimate, namely reputational gains. These can arise from consistently delivering a high-quality service to the customers and building a positive perception among them. This can lead to increased trust and credibility, which may positively impact the overall success of the project.

First, in order to demonstrate the project's feasibility, one generic case will be presented based on the value of the printable component. Since the price of a cabin part can vary, three specific cases will be conducted considering Component Value (CV) = 200, 400 and 600. For each case, the costs will be presented in function of the number of printed parts. Afterwards, four specific case studies will be conducted, considering two distinct airline realities: SATA Internacional – Azores Airlines and KLM Royal Dutch Airlines. The examination of these practical cases will enable comprehension of the best-case scenario for this project's implementation and extrapolate conclusions regarding its profitability.

For every case, the employees' salaries per year were calculated considering 14 months. These values were estimated based on data from job search platforms. Also, the costs related to hardware, software, quality control equipment, training and hiring of a blockchain development company were estimated based on the experience my supervisor has in the field of blockchain development applications.

### General Case

To determine the value of  $C_d(x)$ , 3 engineers ( $p_{IT}$ ) were considered, each one earning 42.000€ per year ( $r_{IT}$ ). The initial hardware and software expenses for the project were estimated to be around 1.000.000€ ( $h + s$ ). For testing purposes, 1 employee was considered ( $p_T$ ), earning 22.000€ per year ( $r_T$ ). The chosen printer illustrated in Figure 10 has important characteristics such as dual extrusion composites for advanced geometries and strong, heat-resistant metal replacement parts. These optimal print conditions allow for an ideal industrial 3D printer able to make parts to be assembled in an aircraft. For this case, only one 3D printer of this type was considered ( $n$ ), costing around 5.000€ ( $e$ ) (“BIG-60 - Impressoras Modix Large 3D” n.d.).

Regarding the material needed, carbon fibre was found to be the most appropriate for 3D printing aircraft cabin parts due to its resistance and strength. Because of these characteristics, this material is widely used in the aviation industry (Shahrubudin, Lee, and Ramlan 2019). In Europe, one carbon fibre filament spool of 500g costs around 40€ ( $f$ ) (“CarbonFil-Black FORMFUTURA Rolo de Filamento de Impressão 3D Composto de Carbono Em PETG de 1.75mm - 500g” n.d.).



Figure 10 - Modix BIG-60 V4 Carbon Fiber 3D Printer

Source: (“BIG-60 - Impressoras Modix Large 3D” n.d.)

The expenses related with quality control equipment were estimated to be around 50€ ( $q_e$ ). For recruiting purposes, 1 HR employee was considered ( $p_{HR}$ ), earning 20.000€ per year ( $r_{HR}$ ). The costs related with training were around 1.000€ per year ( $t$ ), and 1.000€ ( $u$ ) were estimated for software updates and bug fixes.

According to Regulation (EU) 2019/2153 on the fees and charges levied by EASA, the approval fee regarding Product Organisation Approval can be found in Table 10. As the dimension of this project is not very large, the first line of the table will be considered, amounting to an annual certification expense of 20.650€ ( $c$ ). An overview of the variable values used for the calculation of  $C_d(x)$  can be found in Table 1.

VARIABLE	VALUE
$p_{IT}$	3
$r_{IT}$	42.000
$h + s$	1.000.000
$p_T$	1
$r_T$	22.000
$n$	1
$e$	5.000
$f$	40
$q_e$	50
$p_{HR}$	1
$r_{HR}$	20.000
$t$	1.000
$u$	1.000
$c$	20.650

**Table 1** - Variable values applied in  $C_d(x)$  under the general case.

Source: Elaborated by the author

Considering these values and a  $CV=200$ , the annual costs of the project as developing the blockchain solution can be determined by equation (4).

$$C_d(x) = 630CV + 5000CV + 110CV + 25CV + 0,2CVx + 0,25CV + 100CV + 5CV + 5CV + 103,25CV \quad (4)$$

Therefore, equation (5) presents the simplified form of equation (4).

$$C_d(x) = 5978,5CV + 0,2CVx \quad (5)$$

Equation (6) is derived from equation (5) by replacing  $CV$  with 200.

$$C_d(x) = 1195700 + 40x \quad (6)$$

Equation (7) is derived from equation (5) by replacing  $CV$  with 400.

$$C_d(x) = 2391400 + 80x \quad (7)$$

Equation (8) is derived from equation (5) by replacing  $CV$  with 600.

$$C_d(x) = 3587100 + 120x \quad (8)$$

To determine the value of  $C_c(x)$  the same values were used for the variables that were already in  $C_d(x)$ , except for the cost of hiring a blockchain development company that was estimated to be 50.000€ ( $b$ ). An overview of the variable values used for the calculation of  $C_c(x)$  can be found in Table 2.

VARIABLE	VALUE
<i>b</i>	50.000
<i>n</i>	1
<i>e</i>	5.000
<i>f</i>	40
<i>q<sub>e</sub></i>	50
<i>p<sub>HR</sub></i>	1
<i>r<sub>HR</sub></i>	20.000
<i>t</i>	1.000
<i>c</i>	20.650

**Table 2** - Variable values applied in  $C_c(x)$  under the general case.

**Source:** Elaborated by the author

Considering these values and  $CV=200$ , the annual costs of the project as contracting the blockchain solution can be determined by equation (9).

$$C_c(x) = 250CV + 25CV + 0,2CVx + 0,25CV + 100CV + 5CV + 103,25CV \quad (9)$$

Therefore, equation (10) presents the simplified form of equation (9).

$$C_c(x) = 483,5CV + 0,2CVx \quad (10)$$

Equation (11) is derived from equation (10) by replacing CV with 200.

$$C_c(x) = 96700 + 40x \quad (11)$$

Equation (12) is derived from equation (10) by replacing CV with 400.

$$C_c(x) = 193400 + 80x \quad (12)$$

Equation (13) is derived from equation (10) by replacing CV with 600.

$$C_c(x) = 290100 + 120x \tag{13}$$

To determine the value of  $G(x)$ , 1 warehouse employee was considered ( $p_L$ ), earning 19.600€ per year ( $r_L$ ). Moreover, the gains of 1 disruption occurrence on the fleet were considered to be 3.763€ ( $na$ ).

The cost of storing one spare part is estimated to be equal or superior to 25 percent of the cost of that part (Azzi et al. 2014). In this case, an average price of 800€ was considered for cabin spare parts. This estimation takes into account the varying costs of different parts, which can range from hundreds to thousands of euros. That said, 200€ ( $g$ ) were assumed as an average cost of stock, per year, of one cabin spare part. On the other hand, the supply chain cost is the price of moving a product throughout the supply chain, including not only transportation expenses but also warehousing and service costs (AhlSELL et al. 2023). This cost is estimated to be 10 percent of the cost of the spare part in question (Rodrigue 2020). Considering the same average price of 800€ of a cabin spare part as in the previous paragraph, a supply chain cost of around 100€ ( $t$ ) was taken into account in this case. An overview of the variable values used for the calculation of  $G(x)$  can be found in Table 3.

VARIABLE	VALUE
$p_L$	1
$r_L$	19.600
$na$	3.763
$g$	200
$t$	100

**Table 3** - Variable values applied in  $G(x)$  under the general case.

Source: Elaborated by the author

Considering these values and  $CV=200$ , the annual gains of the project can be determined by equation (14).

$$G(x) = 98CV + 18,815CVx + CVx + 0,5CVx + 0,05CVx + CVx \quad (14)$$

Therefore, equation (15) presents the simplified form of equation (14).

$$G(x) = 98CV + 21,365CVx \quad (15)$$

Equation (16) is derived from equation (15) by replacing  $CV$  with 200.

$$G(x) = 19600 + 4273x \quad (16)$$

Equation (17) is derived from equation (15) by replacing  $CV$  with 400.

$$G(x) = 39200 + 8546x \quad (17)$$

Equation (18) is derived from equation (15) by replacing  $CV$  with 600.

$$G(x) = 58800 + 12819x \quad (18)$$

### Case 1: SATA Internacional – Azores Airlines

SATA Internacional- Azores Airlines is a Portuguese airline that plays a crucial role in the development of the Autonomous Region of the Azores. In 2022, the company had 652 employees and 8 aircraft (SATA Internacional – Azores Airlines 2022). For this case, the values were selected considering SATA's framework and Portugal's socio-economic environment.

To determine the value of  $C_d(x)$  for the first year of the project, 3 engineers ( $p_{IT}$ ) were considered, each one earning 27.000€ per year ( $r_{IT}$ ). The initial hardware and software expenses for the project were estimated to be around 1.000.000€ ( $h + s$ ). For testing purposes, 1 employee was considered ( $p_T$ ), earning 22.000€ per year ( $r_T$ ). Considering that, in this case, the project is being applied in a small company, only one 3D printer was considered ( $n$ ), costing 5.000€ ( $e$ ). The price of carbon fibre was considered to be 40€ ( $f$ ), as the cost of one 500g spool.

The expenses related with quality control equipment were estimated to be around 50€ ( $q_e$ ). For recruiting purposes, 1 HR employee was considered ( $p_{HR}$ ), earning 20.000€ per year ( $r_{HR}$ ). The costs related with training were considered to be around 1.000€ per year, every two years ( $t$ ), since some of the required training might be valid for more than one year. For software updates and bug fixes, 1.000€ ( $u$ ) were estimated for the first year of the project since it is when the project will be developed from zero and more occurrences of this type might arise. This estimation assumes that every week, a developer would spend two extra work hours fixing bugs or updating software. Lastly, for the annual certification expense, 20.650€ ( $c$ ) were amounted according to the approval fee regarding Product Organisation Approval found in Table 10 of Regulation (EU) 2019/2153 on the fees and charges levied by EASA. An overview of the variable values used for the calculation of  $C_d(x)$  can be found in Table 4.

VARIABLE	VALUE
$p_{IT}$	3
$r_{IT}$	27.000
$h + s$	1.000.000
$p_T$	1
$r_T$	22.000
$n$	1
$e$	5.000
$f$	40
$q_e$	50
$p_{HR}$	1
$r_{HR}$	20.000
$t$	1.000
$u$	1.000
$c$	20.650

**Table 4** - Variable values applied in  $C_d(x)$  under SATA's case.

**Source:** Elaborated by the author

To determine the value of  $C_c(x)$  for the first year of the project, the same values were used for the variables that were already in  $C_d(x)$ . Additionally, the cost of hiring a blockchain development company was estimated to be around 50.000€ per year ( $b$ ). An overview of the variable values used for the calculation of  $C_c(x)$  can be found in Table 5.

VARIABLE	VALUE
$b$	50.000
$n$	1
$e$	5.000
$f$	40
$q_e$	50
$p_{HR}$	1
$r_{HR}$	20.000
$t$	1.000
$c$	20.650

Table 5 - Variable values applied in  $C_c(x)$  under SATA's case.

Source: Elaborated by the author

To determine the value of  $G(x)$  for the first year of the project, 1 warehouse employee was considered ( $p_L$ ), earning 19.600€ per year ( $r_L$ ). According to internal data provided by SATA's maintenance team, around 196 seats are not sold, every year, due to broken parts ( $n$ ). This value was obtained by multiplying the number of inoperable seats per year in the fleet with the time it usually takes to get the seat back in operation and the average number of an aircraft's daily flights. Considering SATA's 2022 annual report (SATA Internacional – Azores Airlines 2022) an annual revenue per seat of 134,40€ ( $a$ ) was estimated. Moreover, the cost of storing one spare part was considered to be 200€ ( $g$ ) and the supply chain cost 100€ ( $t$ ) per part.

This project focuses on small plastic parts from the cabin, namely armrests and meal tables. Based on the information provided by the airline's maintenance team, damaged meal tables are the most common plastic part related issue that causes seats to become inoperable. Taking this information into account, the calculations will be performed considering the cost of a meal table, which is 342,38€ ( $f$ ) (Kamber 2019). An overview of the variable values used for the calculation of  $G(x)$  can be found in Table 6.

VARIABLE	VALUE
$p_L$	1
$r_L$	19.600
$n$	196
$a$	134,40
$g$	200
$t$	100
$f$	342,38

Table 6 - Variable values applied in  $G(x)$  under SATA's case.

Source: Elaborated by the author

### Case 2: KLM – Royal Dutch Airlines

KLM- Royal Dutch Airlines is the oldest airline in the world still operating under its original name. In 2022, the company had around 28.000 employees and 172 aircraft (Air France KLM Group 2023). For this case, the values of the employees' salaries were selected considering KLM's framework and The Netherlands' socio-economic environment. The other values were considered the same as in case 1.

To determine the value of  $C_d(x)$  for the first year of the project, 3 engineers ( $p_{IT}$ ) were considered, each one earning 50.000€ per year ( $r_{IT}$ ). The initial hardware and software expenses for the project were estimated to be around 1.000.000€ ( $h + s$ ). For testing purposes, 1 employee was considered ( $p_T$ ), earning 40.000€ per year ( $r_T$ ). Considering that, in this case, the project is being applied in a bigger company, two 3D printers were considered ( $n$ ), costing 5.000€ each ( $e$ ). Regarding the price of carbon fibre, the same amount was considered as in case 1, with 500g costing around 40€ ( $f$ ). The expenses related with quality control equipment were also estimated to be around 50€ ( $q_e$ ).

For recruiting purposes, 1 HR employee was considered ( $p_{HR}$ ), earning 40.000€ per year ( $r_{HR}$ ). As in case 1, the costs related with training were considered to be around

1.000€ per year, every two years ( $t$ ). For software updates and bug fixes, 1.000€ ( $u$ ) were estimated for the first year of the project and 20.650€ ( $c$ ) for annual certification expenses. An overview of the variable values used for the calculation of  $C_d(x)$  can be found in Table 7.

VARIABLE	VALUE
$p_{IT}$	3
$r_{IT}$	50.000
$h + s$	1.000.000
$p_T$	1
$r_T$	40.000
$n$	2
$e$	5.000
$f$	40
$q_e$	50
$p_{HR}$	1
$r_{HR}$	40.000
$t$	1.000
$u$	1.000
$c$	20.650

**Table 7** - Variable values applied in  $C_d(x)$  under KLM's case.

**Source:** Elaborated by the author

To determine the value of  $C_c(x)$  for the first year of the project, the same values were used for the variables that were already in  $C_d(x)$ . Additionally, the cost of hiring a blockchain development company was estimated to be around 50.000€ per year ( $b$ ). An overview of the variable values used for the calculation of  $C_c(x)$  can be found in Table 8.

VARIABLE	VALUE
$b$	50.000
$n$	2
$e$	5.000
$f$	40
$q_e$	50
$p_{HR}$	1
$r_{HR}$	40.000
$t$	1.000
$c$	20.650

**Table 8** - Variable values applied in  $C_c(x)$  under KLM's case.

**Source:** Elaborated by the author

To determine the value of  $G(x)$  for the first year of the project, 2 warehouse employees were considered ( $p_L$ ), earning 36.400€ per year ( $r_L$ ). As the airline does not publicly disclose the exact number of unsold seats each year resulting from broken parts, an estimation was conducted by scaling SATA's figures to match the size of KLM's fleet, which turned out to be around 6174 ( $n$ ). This value was obtained by multiplying the number of inoperable seats per year in the fleet with the time it usually takes to get the seat back in operation and the average number of an aircraft's daily flights. Considering the airline's 2022 annual report (Air France KLM Group 2023) an annual revenue per seat of 88,02€ ( $a$ ) was estimated. Moreover, the cost of storing one spare part was considered to be 200€ ( $g$ ) and the supply chain cost 100€ ( $t$ ) per part.

Both SATA and KLM fleets operate recent aircraft, so it is possible to affirm that the cost of their spare parts will be similar. Taking this information into account, the cost of a meal table was considered the same as in case 1, amounting to 342,38€ ( $f$ ) (Kamber 2019). An overview of the variable values used for the calculation of  $G(x)$  can be found in Table 9.

VARIABLE	VALUE
$p_L$	2
$r_L$	36.400
$n$	6174
$a$	88,02
$g$	200
$t$	100
$f$	342,38

Table 9 - Variable values applied in  $G(x)$  under KLM's case.

Source: Elaborated by the author



CHAPTER IV- RESULTS

In this chapter the results of the case studies previously described are presented. As the values on the y-axis cover a very wide range, all graphics are shown in logarithmic scale to make the project outcomes more perceptible and clearer to visualize.

General Case

Figure 11 presents the costs and gains associated with the project considering a component value of 200 euros.

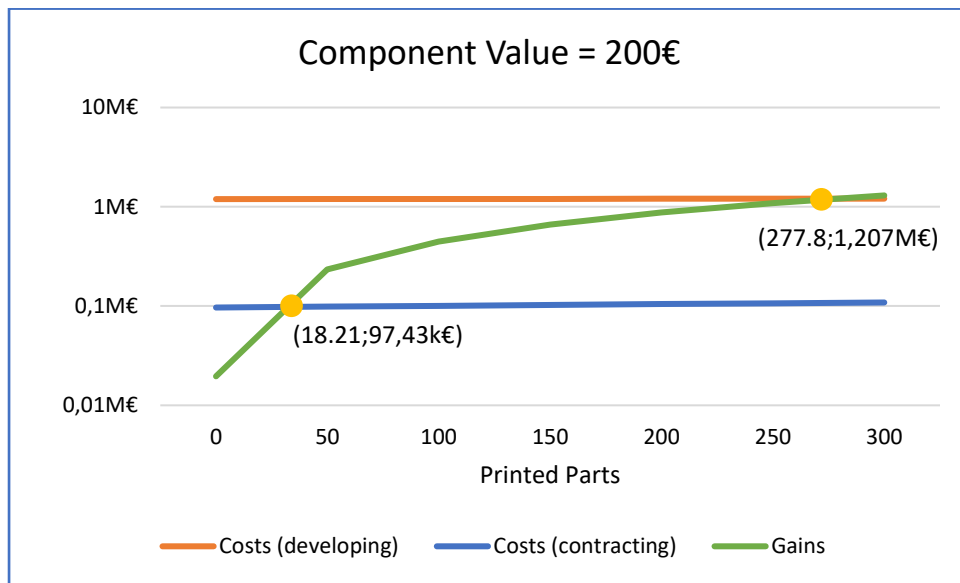


Figure 11 - Costs and Gains per printed parts considering a Component Value of 200€

Source: Elaborated by the author

Figure 12 presents the costs and gains associated with the project considering a component value of 400 euros.

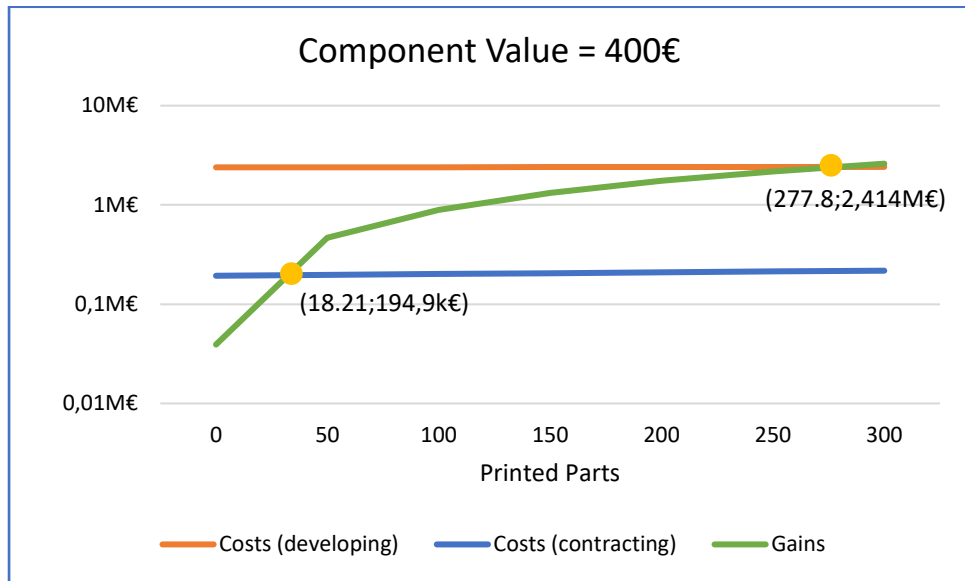


Figure 12 - Costs and Gains per printed parts considering a Component Value of 400€

Source: Elaborated by the author

Figure 13 presents the costs and gains associated with the project considering a component value of 600 euros.

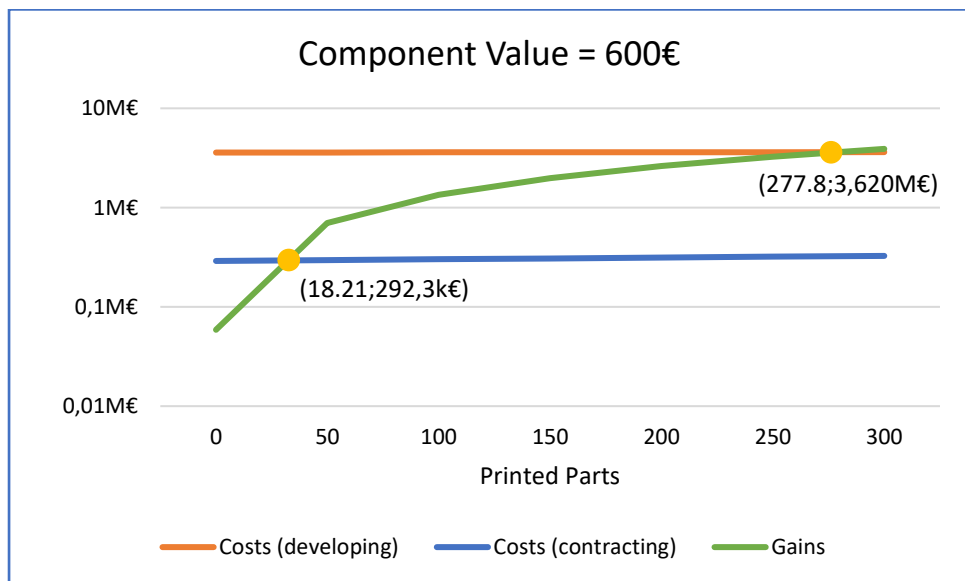


Figure 13 - Costs and Gains per printed parts considering Component Value of 600€

Source: Elaborated by the author

In all three cases, there is a considerable discrepancy between the project cost considering the self-development of the structure in blockchain and the cost considering the external hiring of it. By opting to contract the blockchain structure, the project proves to be more cost-effective. This allows for a quicker breakeven point, which, for every case, occurs at 18.21 printed parts. In contrast, when internally developing the blockchain structure, the breakeven point is only reached after producing 277.84 printed parts regardless the component value. The main difference that exists in these cases resides in the gains, although the costs also increase with higher CV. For CV=200€, the first breakeven occurs at 97,429 € and the other at 1,206,814 €. For CV=400€, the first breakeven occurs at 194,857 € and the other at 2,413,627 €, and for CV=600€, the first breakeven occurs at 292,286 € and the other one at 3,620,441 €.

These results make sense since the costs increase proportionally with the CV and the gains depend directly on the price of the component (in  $G(x)$ ). The more expensive the component, the greater the gains.

In order to assess the project's implementation, a practical application of this model will be developed into 4 case studies. For that, one single cabin part had to be considered so that the costs could be quantified. After discussing this matter with SATA's maintenance team, the part that was most suitable for appliance in this project was the meal table, since it is the part that gets damaged more often in the fleet and that causes more constrains until being repaired. According to the engineers, sometimes it takes up to 2 or 3 weeks for them to conclude the replacement process and put the seats back into normal operation.

Since it was not possible to obtain the cost of one meal table from SATA's aircraft, the Recaro bi-fold seat table P/N 470-00-500-01 used in the economy class of the Boeing 777 fleet in KLM was considered for both cases. Both SATA and KLM have recent fleets and new aircraft, so the costs of materials can be expected to be similar.

As shown in Figure 14, the Recaro bi-fold seat table is positioned at the back of each aircraft seat. It has a closing hook mechanism to firmly secure the table to the seat as well as a hinge mechanism for opening and shutting the table. If the table cannot

comply with these requirements and, consequently, cannot be closed or properly attached to a seat, that specific seat gets blocked and cannot be sold. When the seat in question is on the corridor side, the entire row is blocked (Kamber 2019). According to data from 2019, there were 9.526 Recaro bi-fold tables in the fleet at that time (Kamber 2019).

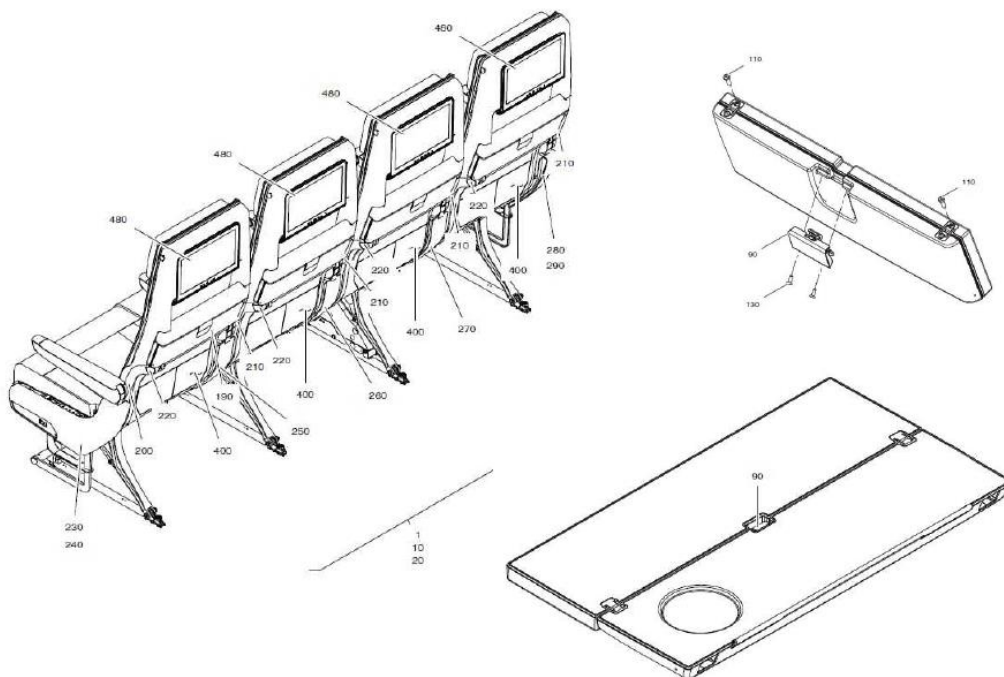


Figure 14 - Recaro bi-fold table

Source: (Kamber 2019)

Each bi-fold seat table costs 342,38€, weighs 584g and has a lead time of 56 days. When 3D printed, this component can be a good candidate to weigh reduction, by using less and lighter materials, reducing wall thickness and applying internal processes like the honeycomb structure that allows to maintain the form of the product while removing surplus materials from its interior (Kamber 2019). If Selective Laser Sintering (SLS) is the 3D printing method chosen, the lead time can be reduced to only 2 days and the weight of this component can decrease in around 9%. When replaced in the whole

fleet, a total of 501kg of weight reduction can be achieved, leading to an annual fuel reduction of 1.503.000\$ (Kamber 2019).

For both distinct realities of SATA - Azores Airlines and KLM - Royal Dutch Airlines, two scenarios were studied, one without considering inflation throughout the years and the other considering an inflation rate of 3% every year. This value was chosen according to the average world inflation rate of the past 10 years by Macrotrends website data.

The inflation rate was applied in the annual salary of personnel and in costs such as hardware, software, carbon fibre material and the price of the original part.

For each case, in the first scenario, the costs were considered constant, and the same as in the first year of the project. However, in the second scenario, those costs vary, taking into account that there are costs that are mostly significant when the project is being started, such as equipment costs. Hardware, software, and 3D printers are examples of initial costs that require a significant investment in the beginning of the project and then only require lower amounts to maintain.

#### Case 1: SATA Internacional – Azores Airlines

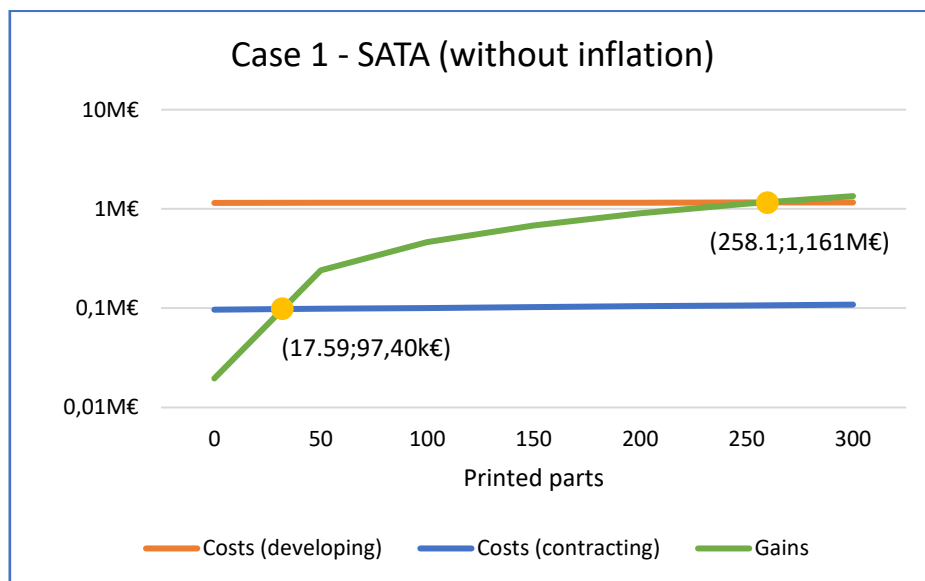


Figure 15 - SATA's costs and gains per printed parts, disregarding the inflation rate

Source: Elaborated by the author

Figure 15 presents the costs and gains associated with the project implemented at SATA - Azores Airlines. The focus is on comparing the costs between developing the blockchain structure internally and hiring it externally. Both cost projections remain relatively stable, regardless of the number of printed parts.

There is a large discrepancy between the project cost considering the self-development of the structure in blockchain and the cost of the same considering the external hiring of the structure. By opting to contract the blockchain structure, the project proves to be more cost-effective. This allows for a quicker breakeven point, which, in this case, occurs at 17.59 printed parts and costs 97,404 €. In contrast, when internally developing the blockchain structure, the breakeven point is only reached after producing 258.09 printed parts and incurring an expense of 1,161,024 €.

These results make sense, since an external company that develops this type of solution for other companies is able to present a lower cost than if the airline itself had to spend all the resources necessary for its development. Contracting an external blockchain structure offers advantages such as reduced overhead expenses and access to specialized expertise and infrastructure. On the other hand, internal development requires investments in resources, research and development, and ongoing maintenance, leading to higher costs. Choosing the contracted blockchain structure not only accelerates the breakeven point but also leads to long-term cost savings. This has significant implications for resource allocation and financial planning, as the internal development approach involves substantially higher costs and a longer breakeven timeframe.

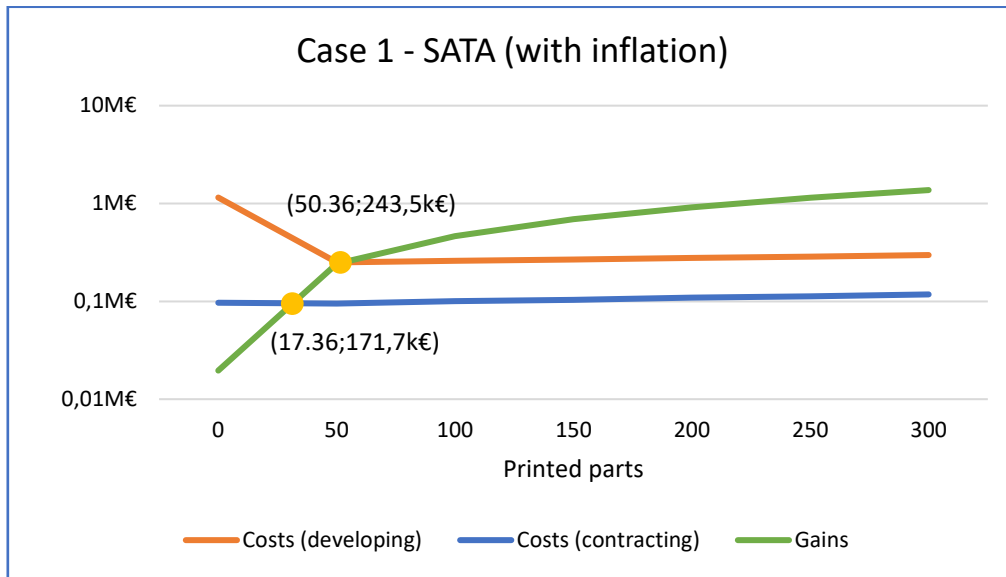


Figure 16 - SATA's costs and gains per printed parts, considering the inflation rate

Source: Elaborated by the author

Figure 16 presents the costs and gains associated with the project implemented at SATA - Azores Airlines, considering an inflation rate of 3% every year. In this case, both cost projections show slight variations with the number of printed parts.

When comparing the costs between developing the blockchain structure internally and hiring it externally, there is a smaller difference observed in this case. This is because, in the external hiring scenario, the annual costs are not constant and the same as in the first year of the project.

Once again, contracting the blockchain structure proves to be the more cost-effective choice. It leads to a quicker breakeven point, which occurs at around 17.35 printed parts and costs 171,655 €. On the other hand, when internally developing the blockchain structure, the breakeven point is reached after producing 50.36 pieces and incurring an expense of 243,468 €. It is important to note that this case analysis aims to present a more realistic scenario by considering the impact of inflation. The 3% annual inflation rate provides a more accurate understanding of the project's financial implications and the changing costs associated with both approaches. This realistic

consideration highlights the importance of factoring in inflation when making financial projections and assessing long-term profitability.

**Case 2: KLM – Royal Dutch Airlines**

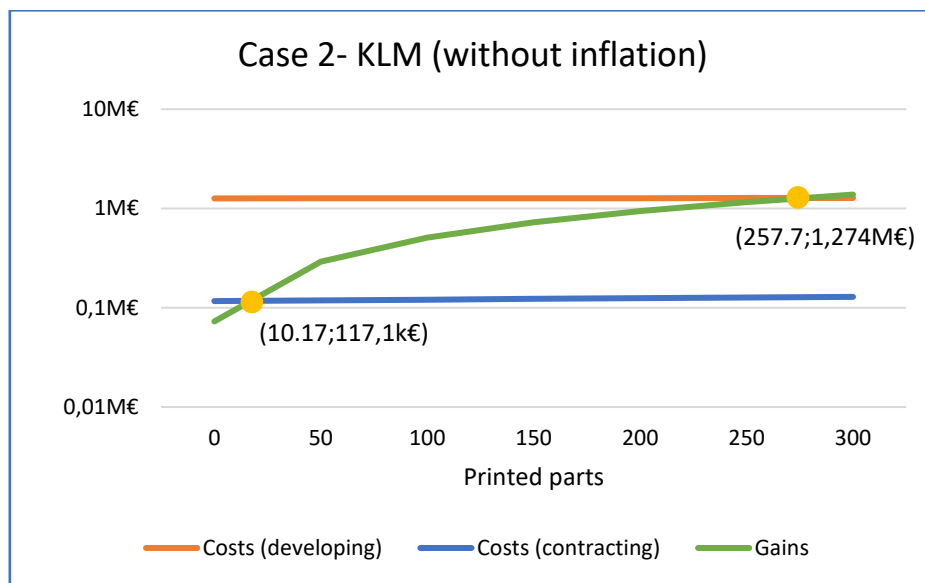


Figure 17 - KLM’s costs and gains per printed parts, disregarding the inflation rate

Source: Elaborated by the author

Figure 17 presents the costs and gains associated with the same project this time implemented at KLM – Royal Dutch Airlines, whilst not considering the inflation rate. Both the costs of developing the blockchain structure internally and the costs of hiring it externally are slightly higher than in Case 1, this because of the salaries of the employees, that are higher in The Netherlands than they are in Portugal.

There is as well a large discrepancy between the project costs, although opting to contract the blockchain structure is still the most cost-effective option for the project. The quicker breakeven point, in this case, can be reached at 10.17 printed parts and costs 117,107 €. In contrast, when internally developing the blockchain structure, the breakeven point is only reached after producing 275.68 printed parts and incurring an expense of 1,273,727 €.

Comparing these results with Case 1, in KLM the breakeven of the project regarding the contract of the blockchain structure is reached quicker than in SATA, while the breakeven of the project considering the development of the blockchain structure is reached later than in the other airline. This may occur because the initial gains of the project in KLM are higher when compared to the initial gains of SATA, although KLM's gains stabilize earlier than in Case 1, indicating a quicker stabilization period. Once more, the impact of employee salaries on the overall gains is a significant aspect to consider, as in Case 2, the gains are notably higher compared to Case 1 due to considerable salary differences between the two cases. These values vary considerably due to the different economic context of both airline countries.

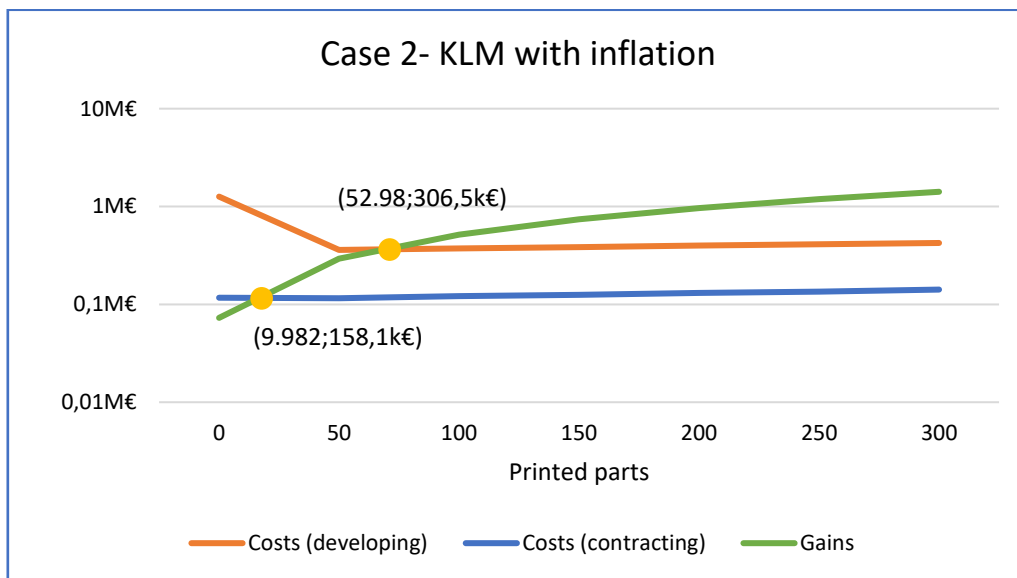


Figure 18 - KLM's costs and gains per printed parts, considering the inflation rate

Source: Elaborated by the author

Figure 18 presents the costs and gains associated with the project implemented at KLM – Royal Dutch Airlines, considering an inflation rate of 3% every year. In this case, both cost projections show slight variations with the number of printed parts, identically to the same projection in Case 1. Also, the costs of contracting the blockchain structure and the costs of developing it internally are more similar when considering the inflation

rate. As well as in the previous projection, in this case both costs are higher than in SATA's Case 1.

Contracting the blockchain solution continues to be the most profitable option for the project, with a quicker breakeven point that, in this case, can be reached at 9.98 printed parts and costs 158,055 €. In contrast, when internally developing the blockchain structure, the breakeven point is only reached after producing 52.98 printed parts and incurring an expense of 306,467 €. The same happens in this projection as in the previous one, with the breakeven of the project regarding the contract of the blockchain structure being reached quicker than in SATA, while the breakeven of the project considering the development of the blockchain structure being reached later than in the other airline.

It is important to note that the analysis of the graphs highlights variations in breakeven timelines and gains between Case 1 and 2. These differences can be attributed to factors such as initial gains, stabilization periods, and the impact of employee salaries. It is crucial to recognize the inherent complexities and considerations involved in implementing a project like this within different airline contexts. Factors such as company size, operational requirements, and maintenance practices significantly influence the feasibility and profitability of initiatives like this. Understanding the contextual nuances and considering a range of influencing variables allows for a comprehensible analysis of the observed outcomes. By considering these factors, informed decisions can be made to implement this project in an adequate context.

When considering the projections with inflation, it becomes evident that implementing the project in KLM yields greater profitability when compared to SATA. The two airlines operate in distinct realities and contexts, with KLM being significantly larger than SATA. KLM has nearly 43 times more employees and a fleet that is approximately 22 times larger, comprising an additional 164 aircraft. This substantial difference implies that in a larger company like KLM, a greater number of printed parts will be required due to the increased number of inoperative seats that the airline experience every year.

The results obtained indicate that in a larger airline such as KLM, the breakeven point can be reached more quickly when compared to a smaller company like SATA. Given that, in bigger companies that may register around 150 occurrences per year, this project could serve as a viable solution for replacing damaged plastic cabin parts. At around 150 printed parts, the gains would be approximately 10 times higher than at the beginning of the project. If these estimations are accurate, KLM could potentially achieve gains of 1,414,723 € by printing 300 parts within two years. Otherwise, since SATA's demand for this specific type of part is estimated to be only around 7 occurrences per year, the costs associated with developing this project may outweigh the benefits when compared to maintaining the existing spare part management system. In Case 1, the breakeven point was reached at 17.35 printed parts, implying that it would take nearly three years, in these conditions, for the company to achieve breakeven and start generating profit.

Furthermore, the implementation of this project in KLM also offers relevant long-term benefits like improved efficiency and reduced downtime. These advantages, along with the expected gains, provide a strong rationale for pursuing the project in the larger airline. The innovative aspect of the project and its positive impact on KLM's reputation, by ensuring that seats do not stay inoperative due to damaged cabin parts, can create a trust and reliable relation between the company and its passengers. On the other hand, SATA's more limited demand for these parts suggests that the costs associated with project development may outweigh the potential benefits. In such cases, it is crucial for smaller airlines like this one to carefully evaluate the cost-effectiveness and practicality of implementing such projects, considering the resources available and the overall impact on their operations.

The analysis of the results regarding both airlines highlights the superior profitability of implementing the project in KLM compared to SATA. The differences in company size and operational context play a significant role in determining the breakeven timelines and potential gains.

In the reviewed case studies, the focus was solely on meal tables, but it is worth considering the inclusion of other cabin parts with similar characteristics, such as armrests, window shades, etc. Expanding the scope to encompass these additional components could facilitate the process of replacing damaged cabin parts to be faster, simpler, and more cost-effective. Considering that more cabin parts could also be printed, the breakeven could be reached even faster due to the economies of scale associated with higher volumes of components. As the volume of production increases, the average cost per unit tends to decrease. This reduction is due to the spreading of fixed costs over a larger output and a more efficient utilization of machinery, labour, and facilities.

As the aviation industry continues to embrace the benefits of 3D printing, it is essential to ensure the quality and functionality of aircraft parts produced through this innovative technology. While blockchain is already being used in the aviation industry for supply chain management, maintenance, flight data, smart contracts, and identity management, 3D printing is revolutionizing spare parts manufacturing and distribution process, enabling faster development, customization while reducing costs and energy consumption. In order to ensure the quality and functionality of aircraft parts, 3D printing should be able to ensure structural integrity, maintaining precision and accuracy. It is also important to use aerospace-grade materials, implement a robust quality control and conduct rigorous tests. Moreover, some certifications will be needed regarding the 3D printing designs of the spare parts in order to prove their credibility.

The results presented by these case studies prove the great potential that DLT technology combined with 3D printing have in the aviation industry. The transparency, security, and traceability of certificate issuance and verification ensured by blockchain can leverage aeronautical certificates to be digitally stored, authenticated, and accessed by whoever needs in a secure and efficient manner. The cost reduction and positive impact on sustainability are also significant advantages of this study. On the other hand, using this technology to issue aeronautical certificates has some limitations, which include the expertise needed that may pose challenges for organizations unfamiliar with

the technology. It may as well require cooperation and consensus among various regulatory entities and industry organizations.

The existing EASA standards and regulations create an opportunity for implementation of DLT and blockchain solutions. Indeed, in airworthiness and parts traceability management, the use and management of data in digital form has no precise definition of these systems, but only global rules on the capabilities that these systems must have. By complying with these regulations, the industry can ensure the authenticity and integrity of digital certificates, which are crucial for the safety and airworthiness of aircraft. Furthermore, an organization that does not hold the Type Certificate for a specific product may produce it under certain circumstances with the authorization of the organization that holds the Type Certificate. The specific conditions and requirements for such authorization are outlined in the applicable regulations and guidelines provided by EASA, which include demonstrating compliance with the relevant airworthiness standards, safety regulations, and quality assurance processes. The organization seeking authorization must satisfy the necessary criteria and undergo an approval process to ensure compliance with the established certification requirements.



### CHAPTER V- CONCLUSION

The results obtained from this study are of significant importance for the future of the aviation industry. The findings demonstrate that the combination of 3D printing and blockchain technology can be revolutionizing in various aspects of aircraft maintenance, certification, and supply chain management. The evidence collected suggests that the proposed system could help decrease the requirement for stocked parts, as well as reduce the downtime of seats caused by waiting for replacement parts.

The utilization of blockchain technology ensures more secure and immutable certification when compared to traditional EASA Form 1 processes, as well as significant cost reductions, increase parts availability and a positive sustainability impact because of weight reduction and no need to transport the parts from the supplier to the end customer. The characteristics ensured by blockchain provide the means for aeronautical certificates to be digitally stored, authenticated, and accessed in a secure and efficient manner. Furthermore, it enables effective tracking and authentication of parts throughout the entire supply chain, thereby mitigating counterfeits and enhancing transparency and reliability in the manufacturing and distribution process. On the other hand, the utilization of 3D printing can possibly contribute to large fuel cost reductions due to the weight reduction of AM printed components in contrast with the original ones.

As it was possible to assess with the case studies developed for this project and their cost-benefit analysis, 3D printing cabin parts and certifying them using blockchain technology has proven to be more cost-effective for larger airlines like KLM compared to smaller airlines such as SATA. This is because in a larger airline with more aircraft, there will be more seats inoperable, per year, due to broken parts. In this case, the gains from implementing the project will outweigh its costs more quickly, as more parts will be printed, and the implementation of the project will have a greater impact on the company.

This project has proven to be a good solution for large airlines with the potential to invest, where, in just one year, it is expected that the gains will exceed the costs incurred. In this situation, the whole process of replacing cabin parts would be revolutionized, positively impacting the various involved departments. On the other hand, in small airlines such as SATA, fewer cabin parts per year need to be replaced, making the gains not worth the investment, since it would only be possible after almost three years for the company to generate profit. In this case, the impact that the project would have on the airline's own operation would be residual.

The fact that the existing EASA standards and regulations provide an opportunity for the implementation of DLT and blockchain solutions, as well as the possibility of issuing a Type Certificate for a specific product makes the proposed project viable among the industry. Investigating the acceptance and adoption of blockchain and 3D printing technologies by airlines and regulatory authorities in the aviation industry would be important to understand the barriers and challenges faced in implementing them. By studying these aspects, it will be possible to create strategies to promote greater acceptance and confidence in the use of these technologies for the manufacturing and certification of aircraft cabin parts.

For the case studies carried out, the meal tables were considered as the main printable part. In the future, more distinct cabin parts with similar characteristics to this one could be 3D printed and integrated in this project as well. In addition, other research perspectives could be explored to further improve the efficiency and feasibility of using these technologies in the aviation industry. New materials are likely to emerge and, as such, research should be conducted to explore their use and to understand if they have different and greater properties than those now in use. The use of such materials could lead to a significant improvement in the performance and safety of 3D printed parts. Moreover, the exploration of future research perspectives, such as the use of sustainable materials, energy-efficient printing processes, and the analysis of the life cycle of printed parts, highlights the ongoing potential for innovation and

improvement in the field of additive manufacturing. These can lead to reduced environmental impact in aircraft production and maintenance.

The implications of the results obtained in this study extend beyond the specific case studies and contribute to the broader understanding of the benefits, challenges, and opportunities associated with integrating 3D printing and blockchain technology in the aviation industry. The findings emphasize the importance of further research and development, collaboration among industry organizations and regulatory authorities, and the need for wider acceptance and adoption of these technologies. With this approach it will be possible to develop more efficient and sustainable solutions to optimize the replacement of damaged parts, improve operational efficiency and reduce costs associated with aircraft maintenance.



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