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# Commercial aviation in a digital world: a cyber-physical systems approach for innovative maintenance

## Abstract

The digital economy is becoming more evident and is redefining customer expectations by bringing innovation not only for everyday life, but also, facilitating the way people work. Movements among different industries are directed through a transformation provided by new technologies such as augmented reality, cloud computing, artificial intelligence (AI), big data, internet of things (IoT), and others. Digital innovations have been reshaping businesses by disrupting existing processes and operating models. One sector that has been embracing digital transformation is the commercial airlines segment. The aviation industry has been investing heavily in technology since its inception. These investments have primarily been driven on the manufacturing side of the industry. Not only must the product digitally evolve, so to must the back office of commercial airlines. Aircraft maintenance is an essential branch for commercial airlines that must renew and adapt to be more efficient, provide greater reliability, reduce costs, and increase availability of the aircraft for revenue service. In this study, the digital transformation brings two key words. The word cyber, as it stands for highly potent mix of digital computing, storage, software, and data networking. Moreover, the word "physical" standing for the entire physical world around as the aircraft systems, people and environment. Therefore, the proposal is to depict today's heavy maintenance process and propose three pictures, aided by cyber-physical systems, which will digitally transform the heavy maintenance process to reduce aircraft downtime in the short, medium and long-term. In order to do so, a proposal of incremental and disruptive innovations will be presented in the context of maintenance management and processes.

**Keywords:** digital transformation, cyber-physical system, airline maintenance management

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## Introduction

The digital economy is becoming more evident in the movements among different industries towards a transformation provided by new technologies. Such technological development in areas as augmented reality, cloud computing, artificial intelligence (AI), big data, internet of things (IoT), and others, are redefining customer expectations by bringing innovation not only for everyday life, but also, facilitating the way people work. By disrupting existing processes and operating models, digital innovations have been reshaping the businesses. This process is called "Digital transformation" and has impacted economies by adding value for industry productivity while bring new challenges for industry and policy-makers.[1] A maturity level of the industry, in respect to digitization, is what defines the successful digital transformation of a company compared to competitors of the same business. The digital maturity level is built upon a combination of two factors, (1) technology innovation related to investments in digital initiatives, which directly influence customer experience, and (2) innovation management related to creation of leadership capabilities to permit the company to move towards a digital transformation path.[2]

Digitization has been happening in different sectors such as banking, telecom, manufacturing, and pharmaceutics. Moving beyond the concept of digital transformation to actual application is a difficult task, especially in terms of what digital technologies enable, and the opportunities they offer to reduce costs and increase profits simultaneously. Thus, not all players have achieved a high level of digital maturity. One sector that has been embracing digital transformation is the commercial airlines. Through extensive investments in innovative services, airlines have improved the user experience and improved customer relationship. Nonetheless, airlines cannot rely only on selling flight tickets, they should keep investing in digital technologies to get ancillary revenue from the entire travel experience–including lodging, rental cars, entertainment, and personalized itineraries – that surrounds the flight. It is important to build digital capabilities to integrate and compel data acquired by travelers. Transforming flights into personalized travel experiences with an interface that makes airlines stand out in a highly competitive market is the challenge faced by this sector.[3]

In addition, full-service airlines have a high level of fixed and operational costs to establish and maintain air services. Fuel, labor, aircraft leasing, engines, spare parts, IT services and networks, airport equipment, airport handling services, sales distribution, catering, training, aviation insurance, are examples of these costs. Thus, a significant portion of the income from ticket sales is paid out to a wide variety of external providers or internal cost centers. One of the important operational costs of an airline is maintenance. Besides the costs related to perform maintenance tasks, which are inevitable, the process of performing heavy maintenance requires the removal of the aircraft from operation during days or even weeks, siting the aircraft in a hangar and not generating any revenue with this asset. However, there is no way to avoid this kind of situation, since the more an aircraft flies the more maintenance it needs, and this process ensures safety for the passengers flying every day.

Hence, the question how to minimize airline down time in heavy maintenance is an important issue for commercial airlines that seek to reduce heavy maintenance costs. Keeping this question in mind, the aim of this project is to analyze the impact of digital transformation on airline aircraft heavy maintenance operations by comparing the picture of today and proposing incremental innovations for a near future improvement and a disruptive innovation as a long-term solution. For this to be accomplished, the plan is to investigate the factors which affect airline operations outcome following planning and control of heavy maintenance, repair and overhaul (MRO), using this information to propose a different heavy maintenance process using the advent of digital transformation.

In this study, the digital transformation comes toward a relationship of two key words. The word "cyber", as it stands for highly potent mix of digital computing, storage, software, and data networking. Moreover, the word "physical" standing for the entire physical world around as the aircraft systems, people and environment. The relation between the digital and the physical world will be addressed using the Cyber-Physical Systems (CPS).[4] CPS is an emerging vision for next-generation information systems that are influencing and transforming the way modern society perceives the physical world, lives, moves, interacts in it, and systems on which human safety and public wellbeing rests. The development of a framework as a starting point has the potential to help understand properties, behaviors, and performance of aviation cyber–physical integrations.[5]

In order to contribute to the solution of reducing labor hours and consequently aircraft ground time in heavy maintenance, a review of its execution process implemented by one of the biggest Brazilian airlines is proposed to understand the actual course of heavy maintenance accomplishment and draw an initial picture of the process.

Afterward, approaching the process with systems engineering, an analysis considering new ways of performing heavy maintenance using a cyber-physical system will take place to highlight two new images, first impacting changes in the near future and second impacting the farthest.[6,7] The idea is to consolidate the physical and cybernetic world into a new process following the studied requirements of the process. The hypothesis is that by using systems engineering to draw today's picture and future's possibilities, a comparison between the actual process and the suggested process, which follows the trend of digital transformation, will be depicted. This assessment offers an indication for a company who intends to apply technology in their heavy maintenance strategy and expects to achieve the much-desired cost reduction. Simultaneously reducing the days out of service and increasing the aircraft availability, which offers an increase in available seat kilometer (ASK), implying an increase in market share by flying more passengers and being more efficient.

## The digital transformation

The world has been changing and transforming through the introduction of new technologies. Every year thousands these technologies arrive to the market and to consumers' hands and often the public have better digital solutions in their own home than at work.[2] Customers today are expecting more from companies, not waiting for a response from their expressed demands, but anticipating their future needs, before they realize them.[8] In the 1990s, the era of information was ahead, and companies were investing millions of dollars in new information technologies (NIT) that helped them to stay competitive, such as websites, mobile communication, teleconferencing devices and other digital technology.[9] However, companies have been worried about spending resources by selecting NITs that deploy the most relevant impact to their business and strategic goals.

The digital transformation strategy is focused on a different approach to IT strategies. It is arriving at a business-centric perspective through new technologies, enabling transformation of processes, products/services, and facilitating the life of workers, supervisors, managers through organizational aspects change.[10] Discussions about digital business strategies offer a base study for the possibilities and effects caused by digitizing firms. Looking forward to succeeding in the digital transformation, leading companies intend to deliver a greater customer interaction and collaboration by focusing on reshaping customer value propositions and transforming their operations through digital technologies.[11] Moreover, digitization depends not only on technology development but also on leadership and innovation management. The strategy should rely on operational and functional strategies that allow the corporate strategy of transforming to be achieved. A combination between both could result in a digital transformation of three main areas of a company: customer experience, operational process, and business model.[2]

Regardless, there are no defined recipes to achieve a complete transformation. Many authors proposed frameworks to understand the level of transformation and build pathways to digitization by observing common patterns in the industry. As an example, Westerman et al.,[12] proposed three elements named the initiation phase, the execution phase, and the coordination phase. Matt et al.,[10] also contributed defining four dimensions of digital transformation strategies that are common among different industries or firms and enables digital transformation, which are use of technology, changes in value creation, structural changes and financial aspects. As well, they outlined the need for management support along the process of transforming once the digital transformation strategy affects the entire company, making leadership skills essential and required to involve the different stakeholders affected. The transition from a traditional to digital era is happening, and companies that do not seize this moment by learning and changing with it will be behind in the market.

According to Westerman,[2] firms that have already begun to gain the benefits of digital transformation can be found in almost every industry, even in small proportion, from pharmaceutical to high technology. Figure 1 classifies different industries in terms of how advanced their digital transformation process is by dividing them into four different levels (1) the beginners that have almost no advanced digital capabilities but could have experience with more traditional applications such as ERP or electronic commerce; (2) the fashionistas are companies that have implemented or experimented with many digital applications; (3) the conservatives who favor prudence over innovation and are typically skeptical of the value of new digital trends, and (4) the digital masters that are firms which truly understand how to drive value with digital transformation by combining transformative vision, careful governance and engagement, with sufficient investment in new opportunities.[2]

Once disruption caused by digitization has an impact on all industries it will be a new set of rules for business.[13] Even some areas that are growing at lower rates, show a significant number of companies acting and investing in this direction.

## The benefits of digitization

Digital mature companies achieve such performance combining two dimensions, digital intensity with transformation intensity. The first is investments in digital initiatives, changing the operations of the firm by technological improvements related to internal and external clients', sometimes even creating new business models. The second is creation of leadership capabilities needed to keep the firm moving towards digital transformation.[2] Azhari et al.,[14] proposed a maturity model for digital transformation to clarify where firms could be situated by depicting five categories of digital maturity (unaware, conceptual, defined, integrated and transformed) and providing guidance for increasing the maturity level thought eight dimensions (strategy, leadership, products, operations, culture, people, governance and technology) shown in Figure 2.

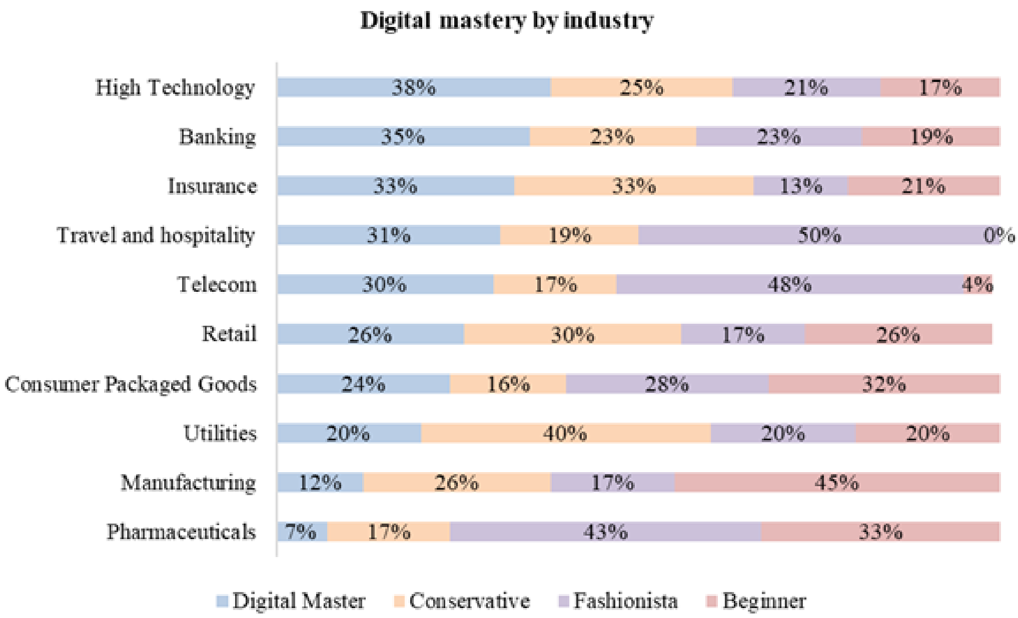


**Figure 1** Digital Mastery by industry.[2]

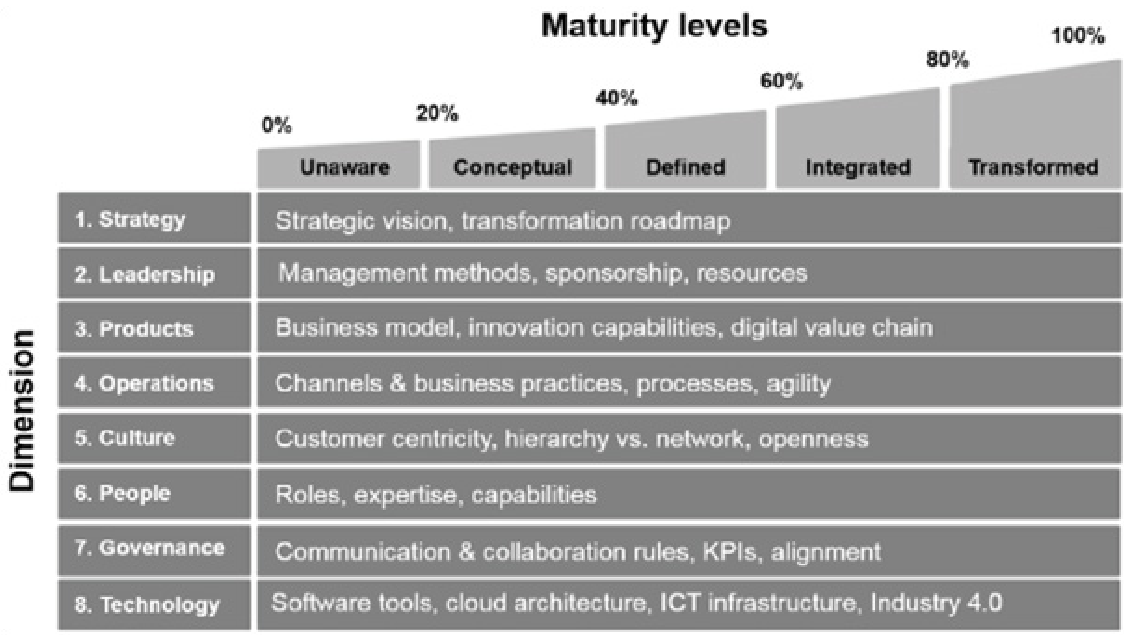


**Figure 2** Digital maturity model of an organization.14

However, why does digital maturity matter? The investments and risks taken by businesses that adopt this movement of transforming digitally must be justified by increases in revenue, profits and/or market share. According to Oestreicher-Singer & Zalmanson,[15] community-based digital business models could create profitable revenue streams in times of "freemium" business models. Another important point brought by a survey of 391 companies, performed by Westerman,[2] is a relation between digital maturity and financial performance. Companies with stronger digital intensity and transformation management are 26% more profitable (considering EBIT margin and Net Profit Margin as indicators) than companies that did not reach digital transformation mastery. This reveals that digital transformation is bringing results to companies that are taking the risk in order to transform.

Since the advent of the web, the aviation industry has been hit by digital competition. These firms have been launching important technological features and have been enhancing the dispute with new business models.

The travel and tourism industry are where the commercial airlines are grouped. They are the only one that does not have beginners in digital maturity graph presented in Figure 2. About 80% of the travel and tourism firms are Digital Masters (31%) or Fashionistas (50%) and the others are Conservative companies (19%). In 2013, one of the richest men in the world, the famous investor Warren Buffett, called the commercial aviation industry a "death trap for investors". Nevertheless, three years later, he spent more than US$ 1.3 billion in commercial airlines stocks, showing the big picture of a new direction in the industry.[3]

The extensive investment in digital innovations prepares firms to reach such levels, but not all of them have invested in transformation management, placing the majority as fashionistas. Notwithstanding, a similar intensity of investment in leadership could drive the travel and hospitality industry through ways to develop a more coordinated and efficient approach, adding value to their digital transformation.[2]

### Aircraft maintenance

An aircraft is made up of millions of parts comprised of complex, redundant systems to ensure safety and reliability of the product. Maintaining these systems costs an airline time and material in conducting thousands of scheduled tasks that must be performed at different intervals, as well as unexpected, or unscheduled tasks.

Some of the current concepts of maintenance types include:

a. Corrective maintenance that is the correction of unexpected failures, these are unscheduled unless they are monitored through the efforts of reliability engineering working to improve or repair the system and eliminating the failure before it occurs;

b. Preventive maintenance which are recurrent maintenance tasks accomplished in order to prevent unscheduled downtime and premature system failures;

c. Predictive maintenance traditionally used solely as a maintenance management tool, which is limited to preventing unscheduled downtime and/or catastrophic failures through regular monitoring of operating condition indicators that will provide the data required to ensure the maximum interval between repairs.[16]

Focusing in preventive maintenance, the classifications of tasks performed in an aircraft mostly consists in inspections, functional tests, operational tests, component replacement, component restore or discard, lubrication, servicing and cleaning. However, around 60% of the total content of maintenance is related to inspections. These inspections could be superficial or internal and take many labor hours to be accessed or require a wide area to be inspected. Two examples of deep access area that are inspected are (1) the fuel tank where valves and pumps are checked to identify leaks, and (2) an extensive area of the fuselage that is examined to identify corrosion or lightning strikes. For the other 40% of maintenance tasks, about 22% are related to functional and operational tests linked to electronic, hydraulic, and other systems. Finally, the last 18% contain component replacements, moving part lubrications, cleaning and servicing. All these tasks are performed to ensure the safety and operability of the aircraft.

Regular maintenance is performed in two different environments:

a) Line maintenance: is performed during overnights when there is no need to remove the aircraft from operation usually requires between 6 and 10 hours of ground time and does not need extensive disassembly.

b) Heavy maintenance or Hangar maintenance: is performed inside the hangar and removes the aircraft from operation, it could require from 1 to 40 days of ground time and extensive disassembles are accomplished.

Aircraft maintenance accomplishment can be viewed in two perspectives, control and performance. Regarding maintenance control, a widely discussed problem is the development of aircraft maintenance schedules, which consists of a complicated process involving the synthesis of a range of economic, political, legal and technical factors. Demand for service, aircraft utilization and operational costs of aircraft are the principal drivers. The goal is to achieve a balanced pattern of flights that results in a timetable consistent with regulatory agency and airline policies.[17] On the other hand, regarding the performance of maintenance, airlines should respect rigorous interval definitions provided by the manufacturer. Most airlines group tasks into check to facilitate maintenance planning and reduce the number of days out of service by knowing when the aircraft must stop flying and trying to set this opportunity together with low seasonal flight requirements. The frequency of these checks depends on a mixture of flight hours, number of take-off and landing cycles, and calendar periods.

Both are part of the same problem, and, despite of a lot of technology embedded in the aircraft systems, most maintenance is still performed through very traditional ways once it is basically related to inspection, and as previously state it requires extensive labor hours and can take days. The digital transformation occurring is bringing technology and a means to change this traditional way of performing and controlling maintenance. Important players of the aircraft maintenance sector are developing business units focused on providing out of the box solutions A great example is the "MRO Lab", a program where all the innovations developed by Air France Industries KLM Engineering & Maintenance (AFI KLM E&M) and its network of affiliates converge.[18] Such a program was tailored to the challenges of aircraft maintenance, where innovations are the fruit of continuous development aimed at satisfying the requirements of airline operating performance.

## Methods

As stated in the introduction, airlines that seek to reduce heavy maintenance costs, face the issue of minimizing down time to increase

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aircraft availability. In order to answer this question, the proposal is to trace the heavy maintenance service requirements of an airline looking at the process of performing maintenance. Listing the steps, labor hours, ground time impact, and costs related to each one. After that, the proposal is to offer a solution through the lens of digital transformation. The following steps were taken to achieve the goal of this work.

## Sample selection

There are different approaches sample selections. As Marshall[19] said, there are three examples of common sample selection methods, convenience sample, judgement sample, and theoretical sample. The method chosen for this work is the judgement sample, which consists in selecting the most productive sample to answer the research question, based on the researcher's practical knowledge of the research area and available literature. The advantage of this method meets the requirements of this work once the subjects (Brazilian airlines) have specific experiences.[19] Air transportation in Brazil was very regulated and restricted. After the 90s, the government started to open price regulations and dictated the way airlines must operate in Brazil.

One of the only governmental limits today is the participation of foreign companies in national airlines, which limits the participation to one-fifth (20%) equity through the Brazilian Aeronautical Code.[20] As a result, the limits imposed by the Aviation Code is a barrier for international companies to be present in the Brazilian domestic market, which more than doubled in the last ten years.[21,22] In Brazil, there are four major airlines that together represent more than 98% of the Brazilian passenger transportation market. The company that transported more passages in 2016 was GOL[23](34.1 % of the total), followed by Latam (32.3 %), Azul[24] (21.9 %) and Avianca (10.4 %).[21,22] To study the maintenance operations of a Brazilian aviation business, and how the digitization may innovate the ecosystem of the sector, GOL's heavy maintenance process was chosen to be analyzed, considering GOL was ranked in 2016 as the leading airline in Brazil based on domestic market share.[21,22] Consequently, it can be considered a representative sample for the purpose of this research.

## Data collection

To collect the date and understand the process, a review of heavy maintenance flowcharts provided by the company is proposed. The data collection was conducted by a review of the latest heavy maintenance flowcharts provided by the company, depicting the steps drawn in these heavy maintenance processes. Observing the method by which the airline regularly performs scheduled heavy maintenance on its aircraft, from when the aircraft is removed from operation and sits it in the hangar, until the moment the aircraft is released to service after being signed by the authorized inspector. The GOL team provided actual maintenance data. In addition to GOL's data, a literature review of available technology to digitally transform heavy maintenance for commercial airlines was included. Using market data from organizations offering products that fit this research proposal, such as systems that provide data analysis, to activities in predictive maintenance of aircraft, ancillary systems that support paperless projects with digital documents, cloud storage and e-signature, web-based system that helps to manage MRO companies.

## Data analysis

The analysis of the data was done considering the current impacts these maintenance processes are causing to the ground time of heavy maintenance checks performed by the airline. Similarly, the validation considered the experience of the company in developing the heavy maintenance flowcharts provided. Focusing on the suggestion of an innovative maintenance process, the analysis starts by describing today's picture of the heavy maintenance process review to comprehend the systems requirements. The review, systems, and requirements analysis were the most important early phase.[25] It allowed the identification of weaknesses that could be improved by digitalization. After underlining the points inside the heavy maintenance process from the airline, the proposal is to use a tool from systems engineering called Systems Modelling Language (SysML) in order to develop a model. SysML enables a more complete modelling of software/hardware systems and facilitates the top-down approach of traditional systems engineering using the block as its primary entity when representing the system in a diagram.[26] There is several software that provides such capability as Papyrus from Eclipse and Arena from Rockwell (open sources software) or MagicDraw from No Magic (commercial software). These products offer a variety of diagrams (e.g. requirement and activity diagrams) that are helpful to obtain a holistic view of the process needed to choose the blocks that could be changed to accomplish the objectives.

Drawing the model facilitates an understanding of the foundations for aviation maintenance problems. Another positive impact from the model is how it can contribute to reducing the ground time of heavy maintenance soon with the advent of digitalization. Proposing which of the system blocks, interconnections, and relationships between the physical and the cyber world can be applied to the existing heavy maintenance process is the goal.

A practical example, given by Trentesaux et al.,[27] of aircraft maintenance using CPS is from the MRO planning perspective. An aircraft on the way from base A to base B recognizes a problem and the decision on where to perform maintenance must be taken into consideration. For example, even though the mechanic and spare parts may be available in base B, an expensive required tool is not. Thus, with the help of software, a suitable tool in base C can be identified and processed through a regular flight from base C to reach base B on time for the maintenance to be accomplished. This interaction between the physical and the cyber world is illustrated in Figure 3.

## Results discussion and data validation

Systems engineering forms a structured development process that proceeds from concept, to production, and to operation, considering both the business and the technical needs of all customers with the goal of providing a high-quality product that meets the user needs. In other words, it is organized to maximize performance. Systems analysis is concerned with the design and construction of processes for complex systems. In possession of the information provided by the airline process, the next step is to identify the flow of the process and its details. In the requirements analysis, processes are defined for the elicitation, management, and linking of desired system properties to ultimately identify points of the process that can be improved by innovative technologies offered by the market.

Adding a cyber-physical relationship to the process provided the overview of the products and applications available to digitally transform maintenance that will be added to the analyzed system in the following chapters.

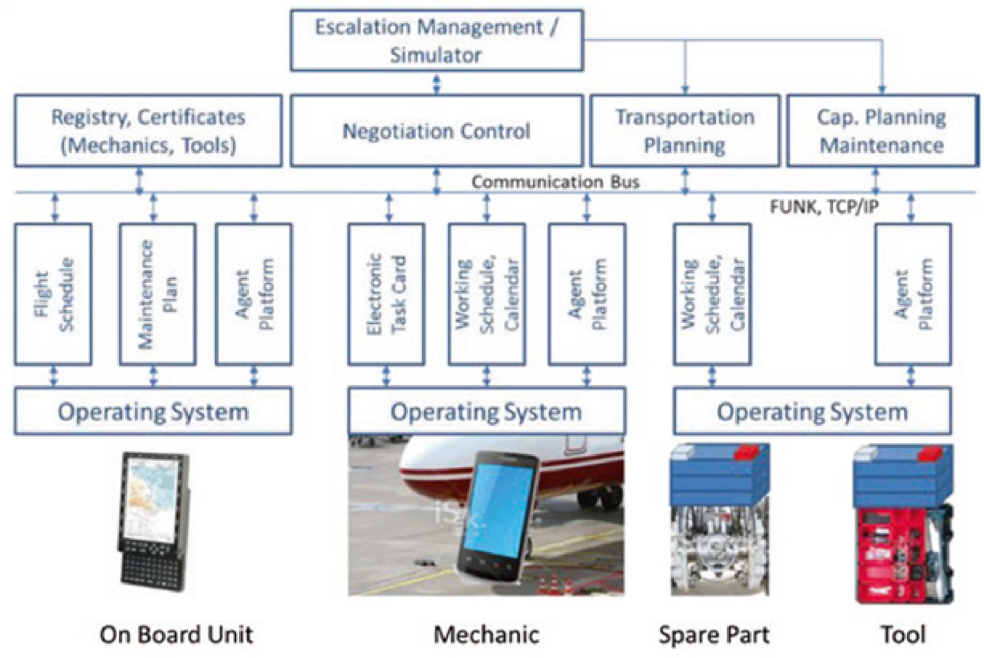


**Figure 3** Architecture of CPS in an aircraft maintenance system.[27]

The understanding of market decisions drives how airlines are conducting their transformation. Results from this phase will provide a holistic view of the heavy maintenance process framework and the possibilities to minimize the ground time of aircraft maintenance aided by the technologies and governance proposed. Once the new system framework is defined and the blocks of the diagrammed process adapted by the aid of the chosen technology, the validation of the data should happen in contribution with the company performing a quantitative analysis of the ground time reduction.[28] Understanding if the improvements proposed are feasible to be accomplished, if it generates a reduction in days out of service during the heavy maintenance of the aircraft and consequently savings for a project of this size to implement.

## Results

The current picture of the airline heavy maintenance process is translated from the flowcharts provided by the company into main steps. These phases are necessary inputs to drawing a picture of where with the maintenance system is today.

### Airline heavy maintenance process review

When an aircraft is manufactured, its maintenance countdown starts. There are three major counters calendar days, flight cycles (that is the number of departures and landings), or flight hours. Based on these three counters, heavy maintenance checks containing scheduled tasks can be created. The process starts with demand planning of the heavy maintenance check. Once the aircraft reaches the planned date for heavy maintenance, the aircraft is inducted into the hangar. At this point, the maintenance is divided into 13 phases that may be performed in parallel. The list of phases is mapped as follows:

1. Pre-docking: site preparation to facilitate access to elevated areas, arranging platforms, scaffoldings, stairs and docks around the aircraft as illustrated by Figure 4.[29] The full process can take up to a few hours;
2. Preliminary inspection: the aircraft is inspected in order to identify visual conditions of structures and systems. Structural damage that can occur in service is verified, such as scratches, buckling, dents, lightning strike damage, etc. In addition, visual condition of system failures is verified, such as leaks, broken parts, missing parts, etc. This phase can also take an entire day to be accomplished;
3. Open access and panels: gain access to deep areas that must be inspected such as stringers, ribs, and spars. For this, it is necessary to remove panels, galleys, lavatories, floors, sidewalls, and overhead bins. The open access phase can take between one and three days;
4. Electrical and hydraulic power off: in this phase electrical and hydraulic power are turned off to ensure safe maintenance of systems that may be pressurized or cause electric shock. Turning off these systems usually takes minutes;
5. Tank defueling: consists of emptying all fuel tanks (wings, center) to gain access to the interior fuel area. This step takes a few hours;
6. Task accomplishment and findings correction: at this point, the aircraft is ready to receive the technicians who will perform the maintenance tasks. This phase takes the most ground time and labor hours to be completed. This step can be divided into four pieces: (6.1) inspections that focus on finding problems, (6.2) task accomplishment that consists of restoring components' original condition, (6.3) opening and (6.4) closing findings that consist in reporting and solving systems or structural problems. The long duration is due to maintenance tasks defined by the manufacturer

that must be performed and all open issues to be corrected in order to ensure that the aircraft will return safely to operation. Depending on check composition and aircraft age, this phase can take between two to thirty days;

7. Close access and panels: installation of all the panels, floors, sidewalls, galleys, lavatories and overhead bins that were removed for inspection. In addition, this action must be carried out with extreme care, ensuring that no tools or equipment are left inside the access areas and that all panels are properly closed. For this reason, an inspection is conducted in parallel to this action. Thus, depending on the number of disassembled panels, this step can take from one to five days;
8. Tank fueling consists in filling all fuel tanks (wings, center). This phase can take a few hours;
9. Operational tests: this procedure is required to ascertain only that a system or unit is operable. These tests should require no special equipment or facilities other than those installed on the aircraft and should be comparable to the tests performed by the flight crews. The entire phase can take five days once it starts during the end of task performance and findings correction phase;
10. Flight test: in the occurrence of primary control surfaces adjustments or sometimes engine replacement, a flight test is mandatory to ensure that the aircraft meets all applicable safety and performance requirements. This phase is entirely dependent on operational issues and usually takes three hours between taxing and performing the flight;
11. Daily and Service checks: checks performed during the last day of the heavy maintenance check and comprises tasks of very low complexity that are executed at a high frequency of repetition, these tasks are related to the checking of routine items such as wheels, brakes, engine oil, potable water and waste, among others. Its duration is about 5 hours depending on the aircraft;
12. Final inspection: the aircraft is inspected in order to visually identify its final conditions. Structural damage that may have occurred during the maintenance period is verified. In addition, visual condition of system failures is verified. This phase also takes an entire day to be accomplished and is the last barrier to avoid post maintenance incidents or accidents during operation;
13. Release to service: this step is the final signature release for the aircraft into service, by ensuring to the aeronautical authority that the maintenance was performed, and the aircraft is ready to return safely to operation. It occurs right after the final inspection and is only a documentation phase.

In possession of this brief explanation, Figure 5 presents an example of a heavy maintenance process flow that visually illustrates a B737-800 heavy maintenance check. The flowchart of Figure 5 can be divided into smaller and more detailed steps, even reaching the facet of each maintenance action that must be performed. However, it is not the goal of this work.

## Systems engineering analysis of maintenance process

The heavy maintenance process review flow chart defines a range of steps that directly affect the ground time of the heavy check. The more complex the step, the more time it takes in the flowchart. Aiming to improve the process visualization and contribute with an answer for reducing heavy maintenance ground time, the phases regarding the procedure of heavy checks were transformed in a system aided by SysML in Figure 6. This system delineates the relationships between the sub processes and tasks serving as a map to guide the discussion on how to use CPS to achieve incremental changes in the current heavy maintenance flowchart.

The joining of Figure 5 and Figure 6 highlights that even small improvement in short duration phases could reduce one day in the heavy maintenance check duration. Saving one day per heavy maintenance check on a large fleet, such as GOL with more than 100 aircraft, would result in a significant increase in aircraft availability for passenger revenue. The data on Table 1 consists of the GOL fleet in 2016 which included 128 aircraft, performing an average of five flights and 11 flight hours per day, with an average of 157 seats per aircraft.[21,22] Considering a load factor of 77.5%, 122 passengers were carried on average for each aircraft.[30]

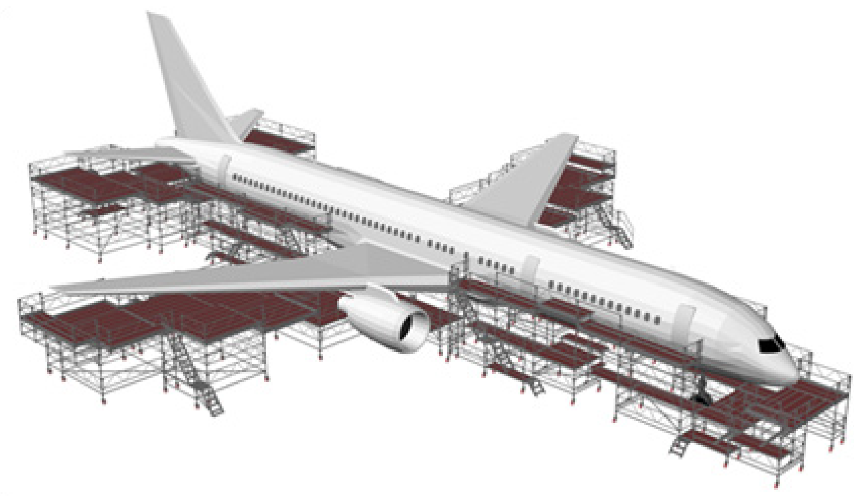

**Figure 4** Aircraft docking illustration.29

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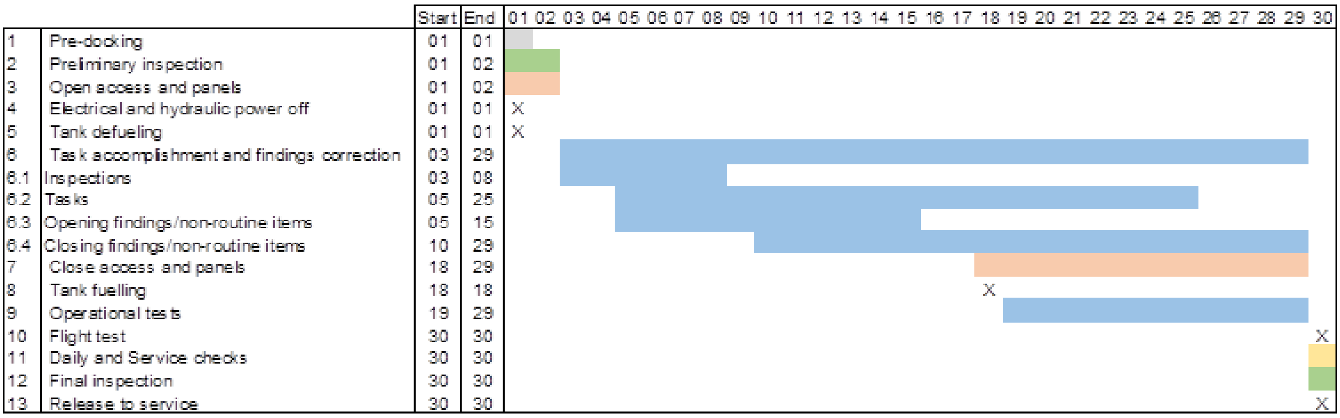


**Figure 5** Example of heavy maintenance flowchart, delineating the different phases of the process.

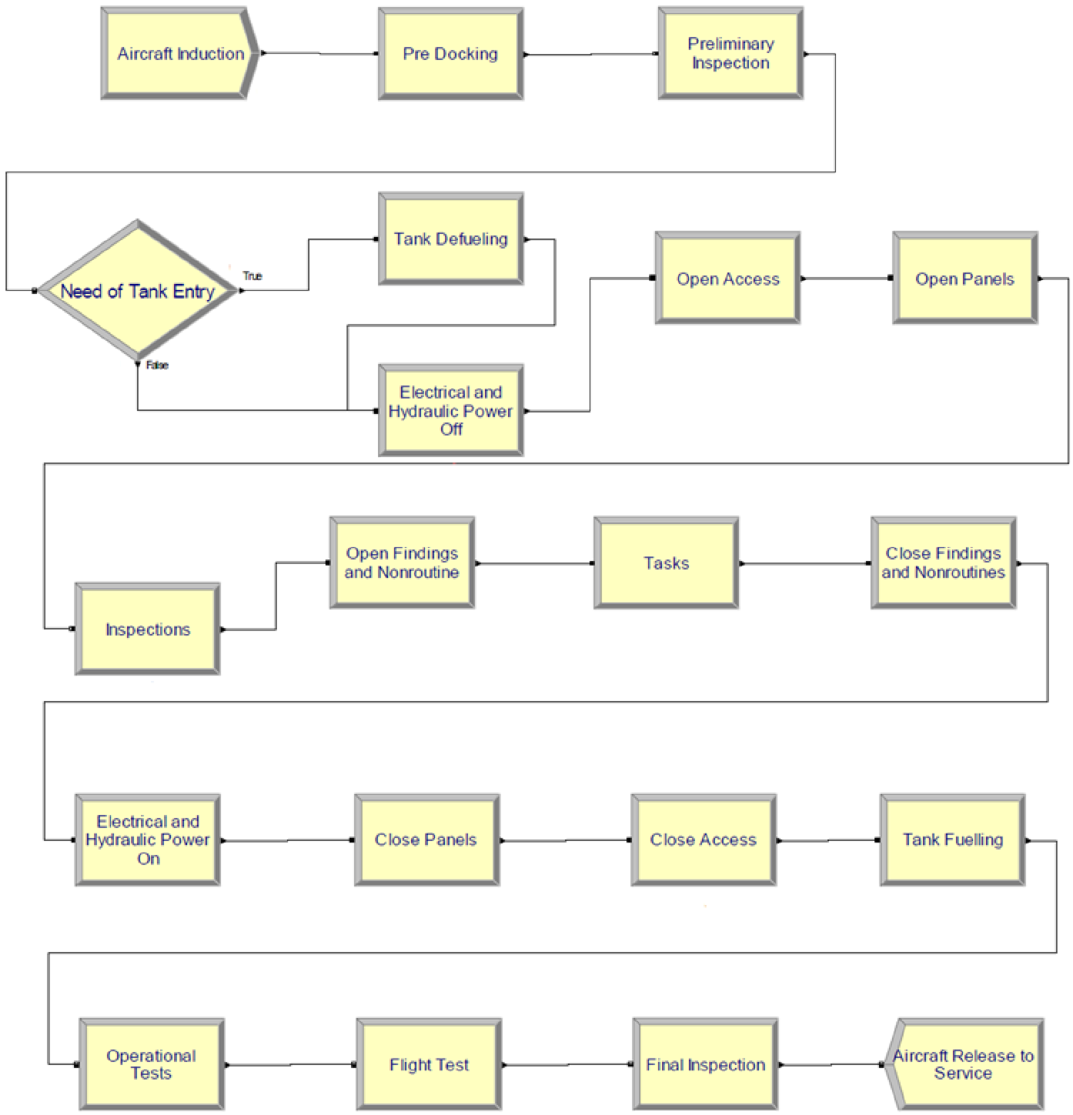


**Figure 6** System depicting the view of today's heavy maintenance process using SysML.

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Considering the data from Table 1, with a gain of one day per aircraft in heavy maintenance per year, it is possible to transport about 77,872 passengers. This calculation was done multiplying one day, times the size of GOL's fleet, times the average flights per day, times the average number of seats, times the load factor. The result represents around one per cent of the total number of passengers that GOL have transported in 2016.[30]

However, this simple calculation has many parameters that can vary with the country's economy, the season when the flights are performed, and other unpredictable things. To avoid such considerations, the path followed in this dissertation considers the average cost of leasing an aircraft. A model to determine airlines optimal mix of leased and owned capacity, developed by Oum et al.,[31] suggests that the optimal demand by these airlines would range between 40% and 60% of their total fleet as a reasonable range of operating lease. Results based on the data from 23 major airlines in the world. Since many airlines lease a considerable portion of their aircraft, the leasing costs for one day of operation can be a good way to measure the avoided costs when saving days out of service.

Using 2016 lease rates to be consistent with the data presented in Table 1, Table 2 presents average lease rates for commonly traded aircraft according to International Bureau of Aviation.[32] Using the data from Table 2, the savings associated with one day of aircraft availability for a Boeing 737-800, similar to those operated by GOL, would range between US$11,000 and US$13,000. Therefore, to reach the next level of performance, it is essential to use technology. Proposing existing solutions of devices and services it is possible to reduce one or more days of heavy maintenance in specific phases that influence total ground time.

**Table 1** Characteristics of participating hospitals[21,22]

| | |
|---|---|
| GOL's Fleet (2016) | 128 aircraft |
| Average flight hours (2016) | 11 hours |
| Average flights per day (2016) | 5 flights |
| Average number of seats (2016) | 157 seats |
| Load factor in % (2016) | 77.50% |

**Table 2** Average leasing rates for commonly traded aircraft in 2016[32]

| Equipment | Low-High Lease rate per month (thousand US $) |
|---|---|
| Boeing 737-800 | 340-390 |
| Boeing 737 MAX 8 | 360-410 |
| Boeing 777-300ER | 1,150-1,450 |
| Boeing 787-8 | 920-1,050 |
| Boeing 787-9 | 1,000-1,200 |
| Airbus A320 ceo | 310-360 |
| Airbus A320 neo | 354-395 |
| Airbus A330-200 | 650-830 |
| Airbus A330-300 | 700-900 |

## Discussion

The solutions proposed will be addressed by digital transformations with the aid of CPSs remediating the problem in three different periods: a short-term innovation by implementing technologies that already exists, a medium-term innovation through technologies that are under development, and long-term innovation by pointing out areas where new technologies would provide additional improvements. All these propositions were based on an ideal model that can potentially minimize the downtime of aircraft heavy maintenance. The ideas were based on GOL practices and how new trends could reshape them.

### Incremental innovation (short-term)

In terms of short-term enhancements that can contribute to the ground time reduction of the heavy check, the proposal is related to an indirect process using software and numerical analysis, providing data to reduce the labor hours spent through revealing the best practices adopted by the most efficient technicians. The airlines can choose among many possibilities to implement software capable of mining big data related to labor hours used to accomplish heavy maintenance tasks. The company can decide whether to develop its own software or buy commercially available products. Big data is a technology that is already contributing to the many fields from marketing to security; therefore, the suggestion must go beyond only identifying best practices.

**Proposed process short-term improvements:** The idea is to use collected data and conduct an analysis to identify divergent task accomplishments during the heavy maintenance. For example, outliers with discrepancies from the sample standard deviation. This will eventually lead to identifying the most efficient technicians. Their practices must be disseminated across the organization. Using this information to develop new methods of performing tasks will contribute to reducing labor hour usage. This labor hour reduction will free skilled labor to work areas that have more demand or, even in small portions, indirectly affect the ground time of the aircraft. The phase of the heavy maintenance process affected are the Task and Close Findings and Non-routines steps, both highlighted in Figure 7.

Keeping this goal in mind, the requirements to perform this kind of change will be divided in two.

1. The first phase is regarding the data mining and analysis, its requirements are:

a. Data accessibility;

b. Human resources reallocation

c. Software support;

2. The second step is about best practices dissemination, which will require:

a. Experienced technical professionals in order to extract the methods of performing maintenance from the technicians with best performance

b. Trainers able to spread the methods among other technicians;

The sub-system of task accomplishment and findings correction are expanded in Figure 8. It is separated in three categories of tasks, and the processes are divided into task accomplishment and findings correction.

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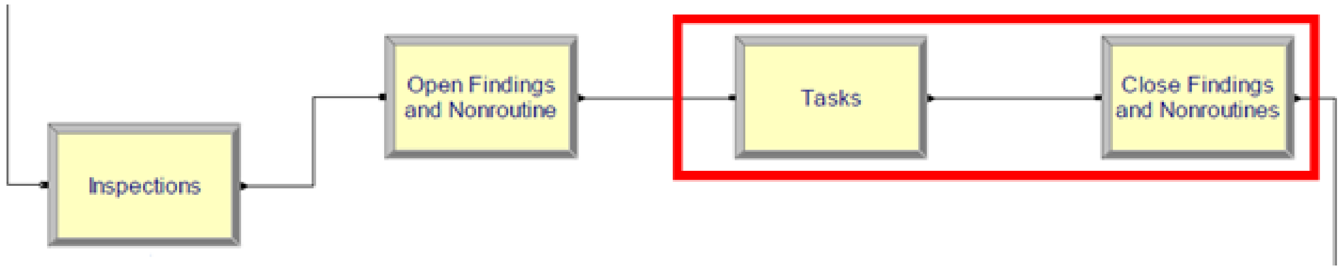


**Figure 7** System depicting the view of today's heavy maintenance process, highlighting inside the red shape the Task and Closing Findings and Non-routine steps, both affected by the proposed implementation.

Changes in this phase, utilizing both labor hour analysis and increased knowledge and methodology sharing, will reduce the duration of task accomplishment and findings correction processes. The result of implementing this kind of analysis can be noted in the longest step of the heavy maintenance process, where tasks are performed. The suggestions seem feasible for an airline such as GOL, with more than ten years of reliable heavy maintenance data, to realize a benefit from expending time gathering and mining this information. As presented in subchapter 5.2, while analyzing the maintenance process with systems engineering, on average, each day out of service saved per aircraft would positively influence the number of transported passengers.

**Cost-benefits of implementing labor hour big data analysis:** Time is a key factor for data analysis, therefore, the longer the company is practicing data collection, the larger its database, and the more accurate the results of the analyses will be. Between the requirements to implement an analysis of labor hour that significantly affects the ground time of heavy maintenance, data acquisition depends entirely on company culture and management of its technical team. Implementing a system that is user friendly can improve the quality of data by helping workers to provide correct information about their task accomplishments.

Starting from the premise that the company providing maintenance is already large enough to attend the following:

1. Allocate a back-office analytics team, a group of analysts that will perform studies to identify the best maintenance performers of each task and will create the training guidelines for this project;
2. A maintenance management software license that must be renovated to keep tracing the labor hours of each task accomplishment;
3. A database of labor hour allocation is already large enough to ensure the quality of analysis;
4. Moreover, the company has a training team already structured and capable of sharing knowledge among the technical teams.

Thus, the costs associated to implement this process would probably already be included in the company structure, causing no impact on cash flow. Since this process change does not cause significant financial impact, a small change in the way data is used translates directly towards the goal of cost reduction, aiding the maintenance management team to be more efficient in their heavy maintenance processes.

For example, from author's experience the standard hands-on efficiency of the mechanics is 65%, assuming that the training developed from the best performers allowed a 10% increase in hands-on efficiency (from 65% to 75%) and the hands-on increase is directly proportional to the number of days, it would result in a 2 days reduction over 20 days in the task accomplishments step presented in Figure 5 and detailed by Figure 8. To be conservative, the author decided to assume only half the benefit is realized, or 1 day, which would represent a reduction of 3.3% in total ground time per aircraft, with no new costs involved for the company. In one year of heavy maintenance, considering a nose-to-tail line or 12 airplanes of 30 days, the savings represent an addition of 12 days of aircraft availability per year. In terms of average leasing cost, the savings would range between US$132,000 and US$156,000.

## Incremental innovation (medium-term)

For instance, the analysis of collected data available today would be enough to perform a project such as described in subchapter 6.1. Considering medium-term progress, the suggestion took place by looking closely at the inspection phases at the beginning of the process highlighted inside the red shape in Figure 9, the two days of preliminary inspections (phase 2) is a great opportunity to be remodeled. If this inspection time is reduced from two days to one day for every heavy maintenance visit, it could represent a significant decrease in the total days out of service, depending on the fleet size.

**Proposed process medium-term improvements:** Preliminary inspection is a visual inspection of the aircraft structural conditions and apparent systems damage. The idea comes from the growing use of unmanned aerial vehicles (UAVs) technology, commonly known as drones, and would represent an incremental innovation in the process. It could contribute to a reduced workload and facilitate the inspection process. The innovative low-cost UK airline EasyJet is said to be experimenting with drones to inspect the fuselages of their airplanes that may or may not have been damaged by lightning strikes. While passengers may not realize the threat of lightening, EasyJet has openly admitted that one of their aircraft gets struck nearly every day of the year. With a drone helping to identify damage, repairs will likely be quicker and more effective.[33]

EasyJet and unmanned-aircraft developer Blue Bear Systems Research made headlines in 2015 when they demonstrated inspecting an airplane by using a drone. By 2018, both partners were close to fielding a system to assist with visual inspections for hail, lightning strike and other damage.[34] The drone flies a pre-planned path around the aircraft to image the surface, carrying various types of sensors to film and interpret unusual conditions as a faster method than walking around and helping engineers locate damage. Not only does this free up the workforce to perform other tasks, but also can result in early release of the aircraft to service.

  

The requirements to implement this idea, which is already being tested by other airlines like EasyJet,[33] are as follow:

1. Match with local regulations of drones use;
2. Trained operator;
3. A UAV capable of support to a visual sensor;
4. A system capable of identifying divergent patterns in the fuselage;

The system implementation flow starts with aircraft induction, followed by the drone preparation phase, then, the drone flight inspection. This inspection will be divided in two possible results, (1) if there is any damage found a damage report must be issued and an inspector will validate the data, (2) if there is no damage found the inspection release would end the process. Figure 10 illustrates the system. The results from implementing this kind of technology will reduce the second step of the heavy maintenance flow. Translating the changes to systems engineering analysis, Figure 9 would reflect the modification of Figure 11.

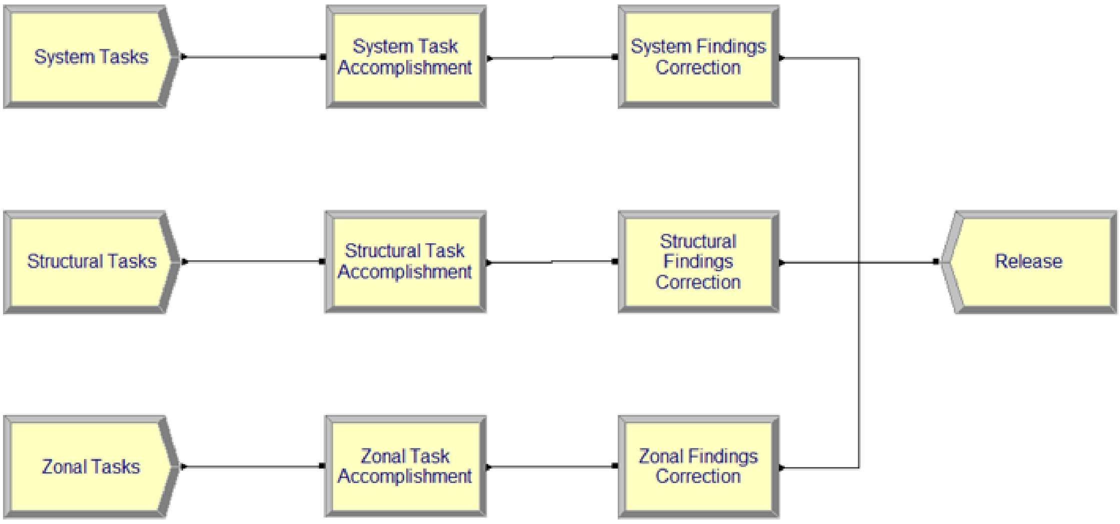


**Figure 8** Sub-system of the task performing level.

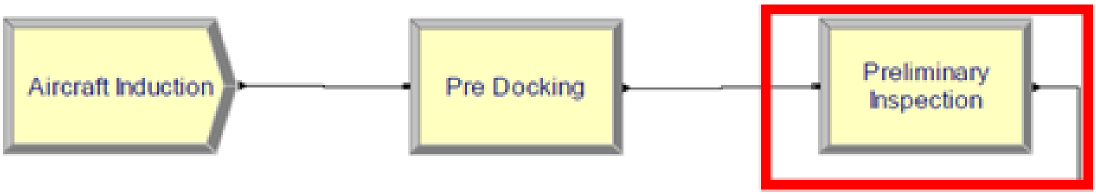


**Figure 9** System depicting the view of today's heavy maintenance process, highlighting inside the red shape the Preliminary Inspection phase affected by the proposed implementation.

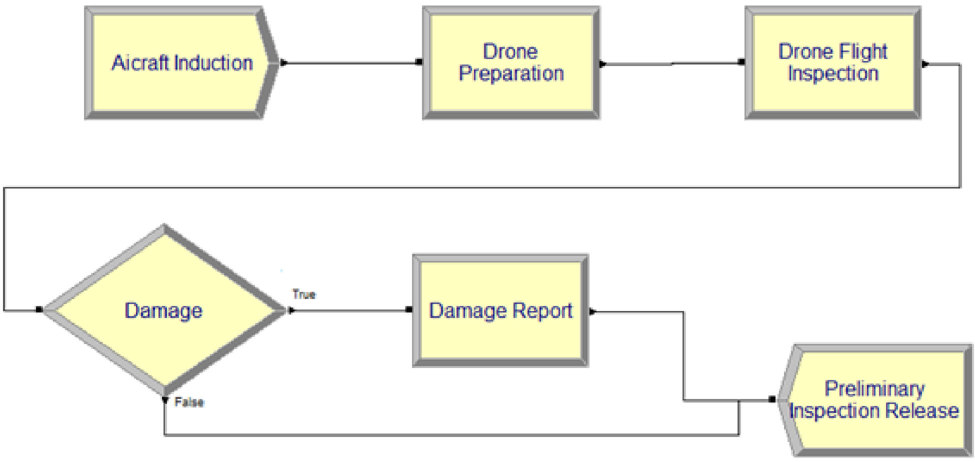


**Figure 10** Proposed system illustration of the UAV preliminary inspection.

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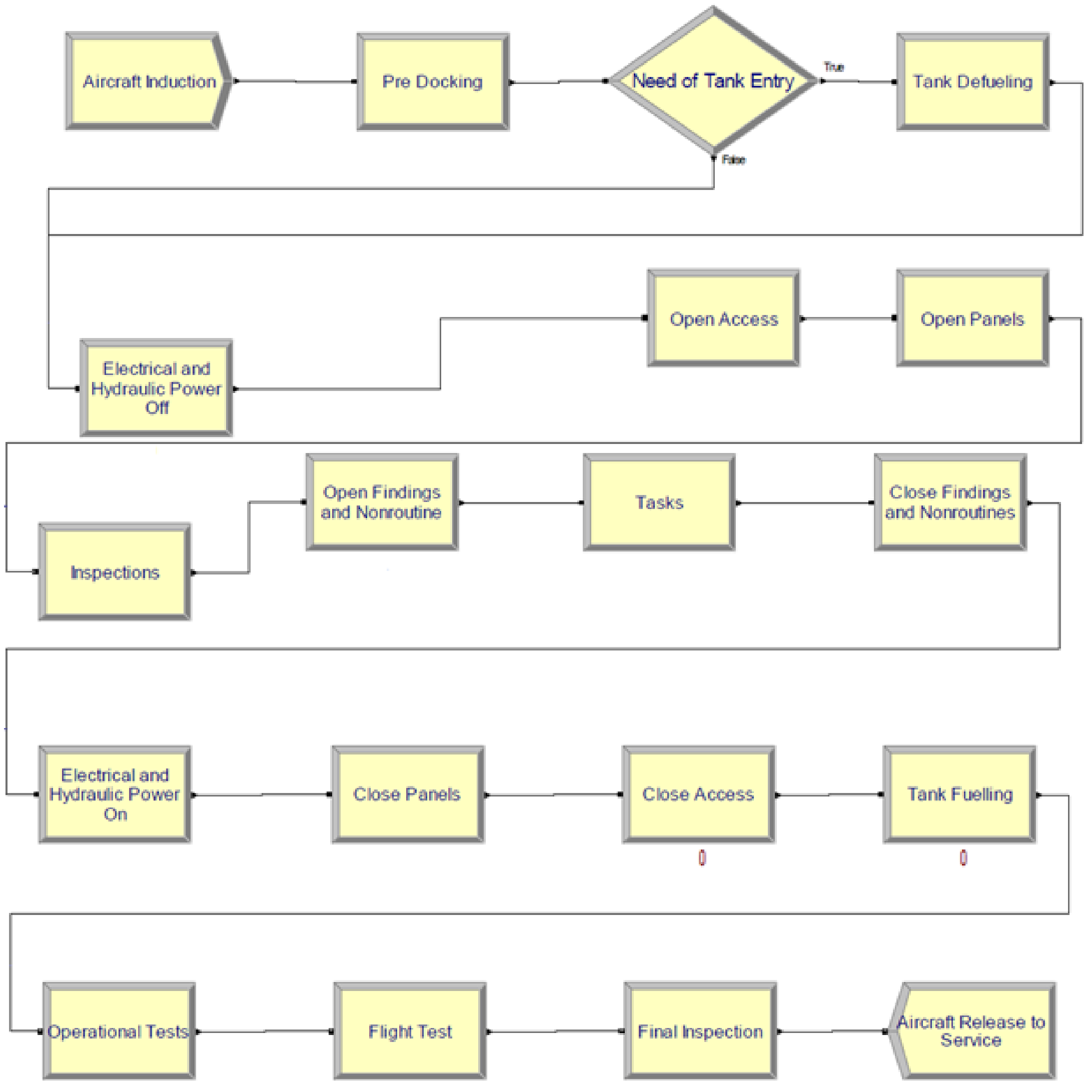


**Figure 11** System depicting the view of heavy maintenance process after implementing the drone preliminary inspection phase, which would reduce one block of the system.

**Cost-benefits of implementing drones for inspection:** Making this alternative feasible requires a cost benefit analysis. Starting with an expenditure review based on the drone implementation process carried out by Scranton Police Department,[8] the main costs related to implementing such innovation include:

1. Initial purchase: Could be directly from the manufacturer, with the example used in this work considering a model that bore a retail price of US$25,000, including the required sensors to perform the inspections;
2. Pilot training: operating a drone is less restrictive, which requires less mandatory flight instruction. Accordingly, pilot training is typically factored by the manufacturer into the purchase price of the drone. This training can cost up to US$3,000, depending on the type of drone and the extent of training required;
3. Pilot certification: operating as pilot-in-command of a drone while earning compensation only requires a Remote Pilot Certificate. While the aircraft maintenance inspector license can cost tens of thousands of dollars, the exam for the Remote Pilot's Certificate costs was estimated at US$150;
4. Pilot hourly cost: for this work, an estimate for the cost of operating a drone for maintenance is US$25 per hour, exclusive of pilot payment;
5. Maintenance and operation: in order to keep the drone operation in safe condition, the costs of purchasing long-term items such as replacement propellers and batteries is estimated to be annually US$10,000 considering 200 inspections with 2 hours duration.

The topics above, summarized in Table 3, were used to estimate the cost of implementing this innovation. In comparison, the benefits of implementing this innovation stem from the timesaving's converted into reduction of aircraft leasing. The estimated result will follow a gain of one day per aircraft in heavy maintenance per year. Considering GOL's 2016 fleet size presented in Table 1, one day per aircraft per year in maintenance corresponds to 128 days, and from that, the possibility to save between US$1,408,000 and US$1,664,000 in leasing days bearing in mind to the data from Table 2.

**Table 3** Estimates of drone implementation costs

| | Cost (US$ per year) | Cost (US$ in 5 years) |
|---|---|---|
| Equipment | 25,000 | 25,000 |
| Pilot training (4 pilot team) | 12,000 | 12,000 |
| Pilot certification (4 pilot team) | 600 | 600 |
| Pilot cost (200 Hrs.) | 10,000 | 50,000 |
| Maintenance & Operation (200 Hrs.) | 10,000 | 50,000 |
| **Total** | **57,600** | **137,600** |

## Disruptive innovation (long-term)

Both proposals presented in subchapters 5.1 and 5.2 are available today and, whether already developed or in development, will support the reduction of heavy maintenance cost impacted by aircraft availability. As set before, the third and last picture drawn in this work aims for long-term improvements through new technologies that are not developed in such a scale to be applied in the next few years. A view of applicable developing technologies that have growth potential was used in this subchapter (5.3) to achieve the goal of reducing heavy maintenance costs by addressing the issue of minimizing down time to increase aircraft availability. That said, the suggestion will be focusing on the longest phase in the process, identified as the task accomplishment and findings correction (phase 6). In this phase, the example in Figure 12 illustrates a 30 days heavy check, where 90% of the total time is spent within this phase as highlighted inside the red box.

Reducing the time of this phase is tempting. However, it represents an enormous challenge as technologies may not exist or techniques may not be possible to be carried out as of this writing. In order to reduce the sixth phase, the key point was to understand what kind of tasks are the ones that take the most time to be accomplished, considering the difficulties in accessing the area and the tools needed to fulfil the requested requirement. After careful consideration, the chosen tasks to be focused on were the structural ones. About 60% of the maintenance program tasks are related to inspections, and from the results in subchapter 5.2 more than two thirds of the total period of the heavy maintenance check is due to inspection tasks, when the structural ones are accomplished.

**Proposed process long-term improvements:** Thinking about this time consumption, the idea is to find a way to identify failures in structures aided by an innovative application of a new technology. The proposed application is to use the graphene circuits' technology to cover internal structures of the aircraft that are difficult to access. Graphene circuits would serve as an indicator of cracks, dents and other damages that, after deforming the circuit or even breaking it, would indicate the position where the circuit was broken, anticipating the need of structural repairs prior to the heavy maintenance check. Depending on how the circuits were applied over the structure surface, it could be also possible to detect the size of the damage.

Some requirements to accomplish such an ambitious goal are list as follows:

1. Develop a graphene circuit capable of adhere to the aircraft structures covered in anticorrosion products;
2. Develop a system that identifies circuit breaks situations and where it is located;
3. Connect the circuit to the aircraft warning system;

This system would significantly decrease the ground time by saving technicians labor hours, reducing the number of access and panels to be opened, dropping the time spent inspecting hidden structural areas, and predicting the best moments to perform the structural heavy maintenance by indicating the right moment to perform the maintenance. The scheme of how the graphene circuit might be applied, starts with an initialization of the aircraft system, followed by a circuit run where current is applied to the graphene circuits. Afterwards the system identifies if there are any structural failures, and if yes, an evaluation of the damage position, turning on independent circuit lines until the line where the failure is located appears as not working. Lastly, if there is no structural failure, or if the failure is located, a report is generated describing the results of the structural check. The system in Figure 13 illustrates the arrangement described.

Applying such a system, which consists of a check designed to be completed in minutes, the result in a heavy check flow reduction was estimated considering two cases (1) 10% of the total ground time by removing the need of deep live inspections, because the system would perform it, and consequently removing the need for 2 days to open access and panels and about 1 day to close them presented on Figure 12 items 3 and 7; and (2) 9 days or 30% of the total ground time by adding the previews case of 3 days with 6 days of inspections presented on Figure 12 items 3 and 7 added with item 6.2.

**Cost-benefits of implementing drones for inspection:** The costs of creating a new system, testing it, and implementing in a fleet is beyond the scope of this work, and would follow a path not foreseen within the objectives of this dissertation. One important point that must be highlighted is that not only the airlines would benefit from such a robust system but also the manufacturers would benefit by reducing their maintenance programs and developing leading technologies, Therefore, both the airline and manufacturer could develop and improve this idea together.

Superficial cost estimations presented here were based on the author's experience and consider the following premises:

1. Research development: computing all phases of development process such as research of technology capability, system design and constructability, testing phase, feasibility of operation and cost of production, the estimated cost would be US$100,000;
2. Large scale production: if the system works as expected, the estimated cost of production of such complex structure would be US$50,000 per system;
3. Implementing the system: to implement the system out of production line it was estimated a cost of about 500 labor hours,

that represents about US$21,000, considering a very conservative and high average price of US$42 per skilled labor hour in Latin America MROs;[35]

The total cost estimated would be about US$150,000 to create the product and US$2,688,000 to install in a fleet similar to the one GOL had in 2016. Besides this cash perspective, there is a period perspective that could be estimated as 6.5 years. The period estimation considers (1) 4 years of research, (2) 2 years of production process developments, system improvements and finding interested companies to apply such innovation, and (3) about 6 months to implement the system and get approval from the aeronautical authorities.

Translating the result from days to savings in aircraft leasing, there are two case scenarios, one for minimum value and another for maximum, both considering GOL's 2016 fleet provided by Table 1 and the average cost of aircraft leasing illustrated in Table 2.

1. The scenario which the system would return 3 days saved per aircraft in heavy maintenance check would save on average a range between US$4,224,000 to US$4,992,000 per year in cost of leasing;
2. The best-case scenario of 9 days saved per aircraft in heavy maintenance check would also save on average a range between US$12,672,000 to US$14,976,000 per year in cost of leasing.

Compared to the total cost of developing and implementing this innovation, the gains would be over US$2,000,000. However, the period to implementing this technology must be considered as a negative.

## Adding-up the proposed innovations

Looking only from the ground time perspective, a decrease was observed for each innovation presented in subchapter 6.1 to subchapter 6.3. In order to best understand whether an airline should implement each one of these innovations, an airline must evaluate implementation of the processes, technologies required to implement and whether it fits their business goals. Nevertheless, considering GOL's perspective, the costs to implement were evaluated in order to demonstrate that these results are feasible. Some estimations of costs related to technology acquisition, implementation and maintenance were addressed in the previous subsections.

With the intention to provide a holistic view of each resulted gained, and how they could be summed to achieve even better savings for the airline heavy maintenance process, a great way to facilitate understanding is to translate the savings in ground time into a figure. Illustrating each gain progressively, by compiling all the proposed innovations previously discussed, as presented in Figure 14. The estimated results of individual proposed innovations have an impact on heavy maintenance check total ground time; however, if explored together, the application of these innovations could achieve even bigger gains. From the illustration in Figure 14, the estimated reduction of about 40% in a nose-to-tail heavy maintenance line would bring an average return of 145 days per year.[36–44]

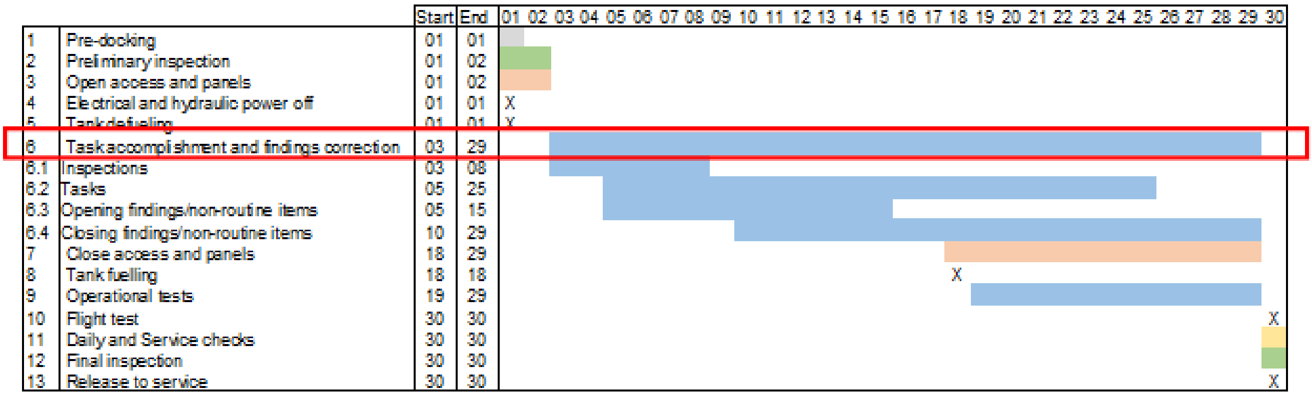


**Figure 12** Example of heavy maintenance flowchart, highlighting the task accomplishment phase with a red box.

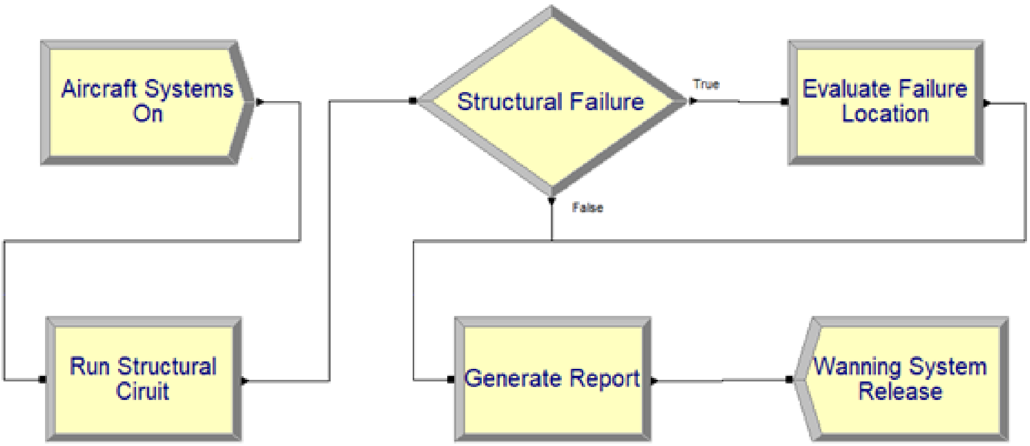


**Figure 13** Proposed system illustration of the graphene circuit integrated with the aircraft system to check structural damage in hidden structures.

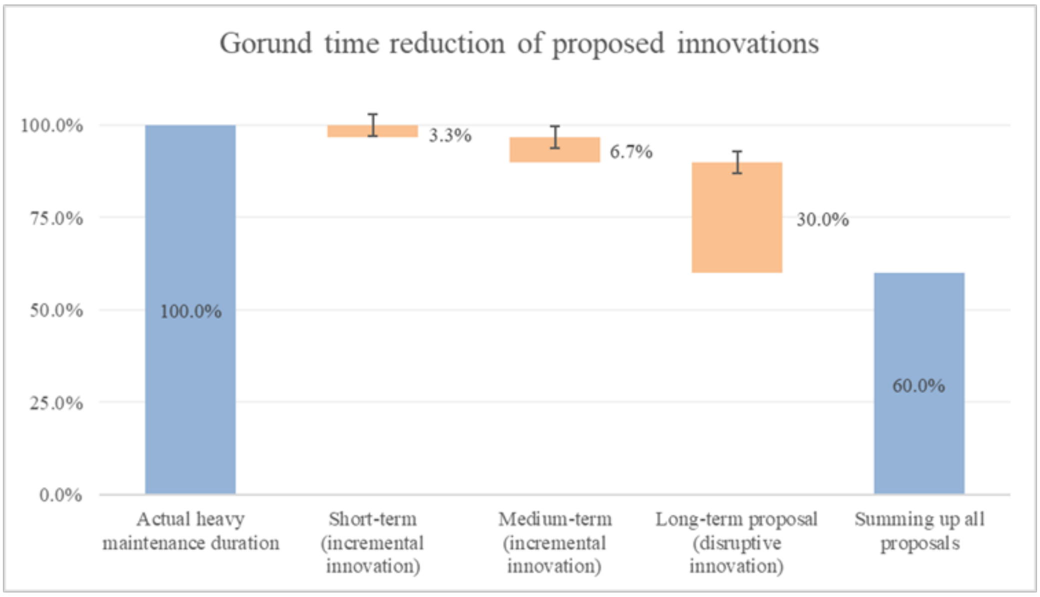


**Figure 14** Ground time reductions illustrating the proposed innovations in the heavy maintenance process, with standard error bars representing the possible deviation in each reduction.

## Conclusion

Digital transformation is happening in many industries. Inside airlines, the solutions to transform digitally are acting within different sectors, from passenger experience, to maintenance timing and performance. Among the airline market, there are different systems that provide improved efficiencies through CPS. However, as observed, there are still many possibilities to upgrade the way maintenance is accomplished. Examining the heavy maintenance process more closely, it was possible to highlight systems that bring incremental innovations by increasing productivity in the short and medium term, ultimately reducing ground time spent in the hangar.

Short-term improvements are the ones airlines should be looking towards implementation while this work is being written. As discussed, many companies are already deploying systems that interact with the surrounding environment to enhance maintenance performance, reduce costs, and be more effective.

Hence, efforts in developing new cyber-physical systems can enable disruption in the way heavy maintenance happens today, predicting the need for maintenance, warning, or even making decisions based on safety prior to human interaction. The academic contribution of this dissertation is to demonstrate that there are still other barriers to be broken in technology development. Ideas may not only be generated from industry but should also emerge from universities and research centers. This dissertation is evidence of the beneficial relationship between digital transformations in aircraft maintenance when discussing the proposed innovations or even when pointing to a disruptive technology.

The contributions to the industry derived from the power that transform digitally would directly affect the cash flow of a company. Technologies responsible for digitization, such as those mentioned in this work, are bringing improved efficiencies to heavy maintenance processes, resulting in reducing costs for airline, and leading to ground time reduction. The expertise derived from mastery of technologies benefits airlines by generating scale effects and optimizing fleet performance. A wave of digital transformation is upon us and this transformation will also improve the methods used in the heavy maintenance management area.

Concluding, the movements towards digitization are accelerating. A cost reduction is possible for those who embrace such changes. Impacts on airlines' cash flow are feasible not only in the long-term but also in the short-term. Therefore, the first companies to achieve a digital mastery level in maintenance will be the first to harvest its benefits, driving the popularization of the connection between human and technology by exploring new possibilities to increase airworthiness and safety. In order to provide a direction for future studies, this dissertation proposes to investigate more thoroughly the impacts of the disruptive innovation discussed in subchapter 6.3. Also, by following the proposed ideas in this dissertation, exploring technologies that will enable the use of such powerful methods by allowing for the application of these future technologies, could result in a new way for how aircraft are maintained in the future. Development of a subsystem like this will be an important step for large-scale applications.

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## Conflicts of interests

Author declares that there is no conflict of interest.

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