



A SUPPORTING FRAMEWORK FOR AIRCRAFT MRO OPERATIONS. CAPACITY PLANNING, TASKS TRACEABILITY AND DISEMBARKED ITEMS TRACKING

Francesco Martone¹, Gaetano Zazzaro¹, Michele Inverno¹, Sergio De Luca², Francesco Mainieri³ & Gianpaolo Romano¹

¹C.I.R.A. Italian Aerospace Research Centre, Capua, Italy

²Atitech S.p.A., Napoli, Italy

³Major Bit Consulting s.r.l., Roma, Italy

Abstract

Aircraft Maintenance, Repair, and Overhaul (MRO) refers to a wide range of services and activities aimed at ensuring safety and operability of the aircraft, including routine maintenance, corrective repairs and extensive overhauls. MRO sector is highly competitive and risky. Aircraft maintenance is a labor-intensive process involving specific tasks and procedures. It begins with inspections and verifications, followed by repairs, replacements, and modifications and ends with final checks and tests to ensure airworthiness and release the aircraft for flight. Maintenance operations are complex, requiring careful planning and scheduling, operational control and specialized skills due to the numerous tasks involved and strict regulations that must be followed to ensure reliability, safety, and airworthiness. This paper addresses work order management in an aircraft MRO company from three perspectives: task traceability for certification, tracking disembarked parts, and task planning. These activities are crucial for improving the efficiency of aircraft maintenance management. We introduce a hardware and software platform for aircraft maintenance management, able to support specialists in analyzing, planning, and scheduling the complex maintenance activities.

Keywords: Aircraft maintenance, assets traceability, blockchain, capacity management.

1. Introduction

Aircraft maintenance, repair and overhaul (MRO) includes all technical services necessary to ensure the safety, reliability, and airworthiness of an aircraft. This includes many activities of routine maintenance checks, corrective repairs and complete overhauls involving inspection, repair, and replacement of parts. MRO activities are fundamental to operational efficiency and compliance with aviation safety regulations [1]. Aircraft maintenance is a labor-intensive process involving specific tasks and procedures, from inspection and verification to repairs, replacements, modifications, and final checks ensuring airworthiness. It requires meticulous work programming, planning, control of operations, and specialized skills to meet stringent regulations and guarantee reliability, safety, and airworthiness [2].

In this paper we address the problem of work order management in an aircraft MRO company from three different points of view: task traceability for certification, tracking of the parts disembarked from the aircraft and task (capacity) planning. All these activities are of paramount importance in improving the efficiency of aircraft maintenance management. We present a platform, both hardware and software, for aircraft maintenance management designed and developed within the CY-MA (CYber-MAintenance) project, an ongoing project co-funded by Ministry of Enterprises and Made in Italy. The project is carried out by a consortium led by Atitech, an Italian MRO, with the collaboration of CIRA, the Italian Aerospace Research Centre, and Major Bit Consulting, an Italian company with experience in the field of ICT consultancy and training.

In Aircraft maintenance, few key parameters measure the competitiveness of MROs: grounding time, cost, and work order completion with zero deferred.

MRO Business lies in the correct work order management, the control of operations allows the efficient resources management, the sharing of work in progress data and information increases

customer satisfaction. To increase performance, an MRO must elevate and strengthen its digital process management systems.

The digital transition in the aircraft maintenance process is underway but, to increase the system competitiveness, greater reliability is needed. The digital data conversion and management must be based on consolidated historical data set, the most advanced technologies such as Artificial Intelligence (AI) and Virtual Reality (VR) can only take place through a process of strengthening systems and organization based on digital culture and intensive use of digital devices which do not represent simple aids but essential tools to guarantee process and service certification.

The project aims to implement a large scale and operationally relevant demonstration and validation of technology, project results analysis is the prerequisite for the necessary confidence for long-term investments needed for service development, and to build confidence among MRO who will purchase and integrate new digital systems in their enterprise resource planning (ERP) tool. By concurrently maturing, integrating and demonstrating viable solutions, the programme will provide the required evidence and confidence for all stakeholders.

The general problem of capacity planning in maintenance has been addressed by Duffuaa et al. in [5], presenting measures for evaluating the adequacy of available maintenance capacity and to propose models and methods for effective maintenance capacity planning. The paper outlines techniques for forecasting maintenance load and classifies maintenance capacity models also highlighting the necessary input data and solution algorithms. In [6], Dinis et al. explore the use of Big Data and predictive analytics to harness the data generated and stored during the planning process for aircraft maintenance interventions in an MRO organization. They implement Bayesian networks (BNs) as a tool to cope with the inherent uncertainty of workload estimation in aircraft maintenance due to the occurrence of unscheduled non-routine activities. Predicting the unscheduled workload in aircraft maintenance is also the main focus of the work by Georgiev et al. [7], they implement a linear regression and two supervised learning models (Random Forest and Support Vector regressors) for workload estimation using historical data, with the former giving the best results. In [8], Dinis et al. introduce a framework based on the analysis of historical data aimed at helping MRO companies with capacity planning and scheduling by providing a comprehensive characterization of maintenance work. The paper by Fabig et al. [9] explores data-analytics methods to provide model parameters for automated capacity planning, using the extensive data in ERP systems. The authors propose a methodology to provide consistent input parameters for daily discrete event simulations.

Blockchain is a decentralized and distributed digital ledger technology that records transactions across many computers in a way that ensures the immutability, security and transparency of the data. Blockchain was born as a technology to be used in cryptocurrencies, but has many applications across various industries [10]. The application of Blockchain technology in the management of aircraft maintenance is an emerging field of research. The work of Efthymiou et al. [11] examines how Blockchain can be applied to airplane MRO industries using a mixed-method approach involving interviews and a case study. They explore the current status of maintenance record management, the benefits of Blockchain for data storage and discuss the barriers in the adoption of this technology in present MRO facilities. In [12], Ho et al. introduce a blockchain-based platform to improve spare parts traceability, data quality, and information security. Efficient aircraft spare parts inventory management is key to airworthiness and regulatory compliance. The system proposed in this work is designed to improve data quality, ensure secure information sharing, and contribute to the creation of a digital twin for the aviation industry. The paper by Inayatulloh et al. [13] explores how blockchain technology can be utilized to enhance aircraft reliability and maintenance processes to improve overall flight safety. It addresses the limitations of current maintenance systems and proposes a blockchain-based framework to address these issues, highlighting that all stakeholders, including maintenance crews, operators, and regulators, can have access to a transparent and immutable record of maintenance activities. Andrei et al. [14] present a blockchain-based network designed for managing aircraft maintenance records. Their network design involves a range of partners including airline companies, maintenance organizations, aviation authorities, manufacturers, and parts suppliers, the authors also describe their interactions for data sharing and consumption.

2. Description of the work

Our work started setting requirements and base criteria in order to develop a digital platform specialized for MRO, to optimize maintenance work flow, with focus on scheduled maintenance activities and associated logistics management integration, to assist organization managing additional and corrective actions for unplanned maintenance activities, increasing the levels of reliability and safety, minimizing the use of paper support and encouraging the use of interconnected and integrated systems aimed at the digital visualization and management of information and actions.

In Figure 1 is represented the general architecture of the platform developed and described in this article, with a depiction of the data flow between its different components. The proposed solution is based on more than one technological application, starting with optimization algorithms or machine learning technology applied on the available databases, providing AI application studies, customized to the aircraft maintenance process (**MRO Planning Tool** for capacity planning).

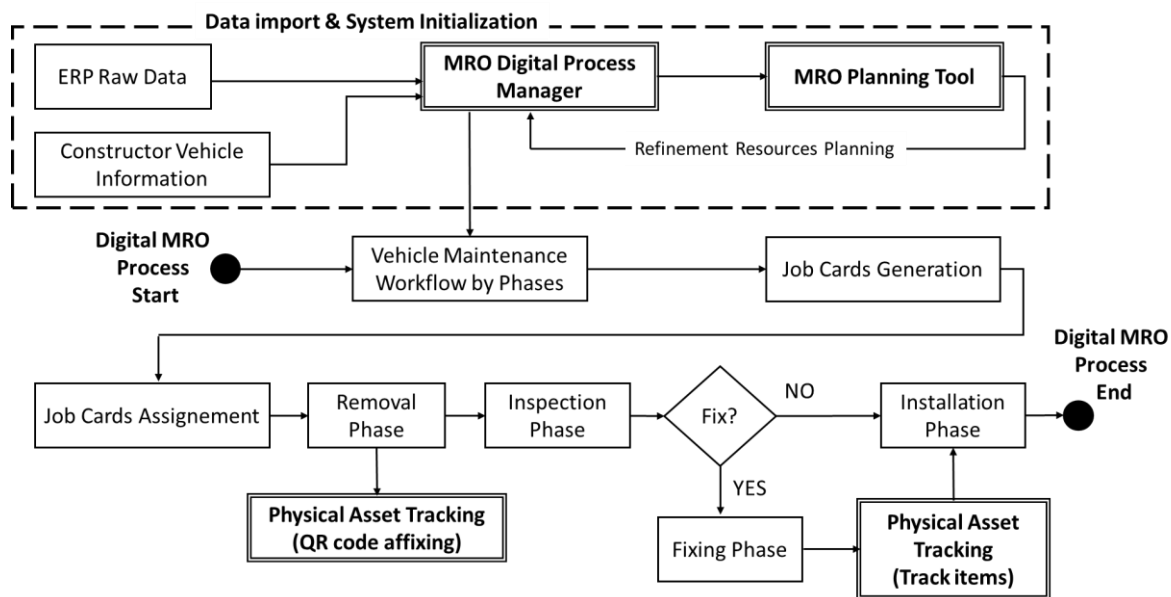


Figure 1 System architecture design.

Another technological direction is based on an original Blockchain application (**MRO Digital Process Manager**), to guarantee the immutability of information and the transparency necessary to certify maintenance operations in a paper-less workflow and to coordinate the different activities in the business process. Furthermore, IoT and Bluetooth technologies are used to implement the traceability of the data relating to the components and parts removed from the aircraft under maintenance (**Physical Asset Tracking**). The project includes developing action to implement a pilot maintenance line for innovation assessment and technology level validation.

3. Capacity planning

3.1 Introduction

The activities necessary to complete the maintenance of an aircraft can be divided into two categories: planned activities, which are those envisaged in the maintenance planning document prepared by the aircraft manufacturers and for which precise execution times are defined in terms of flight hours or flight cycles, and the so-called non-routines, which are unforeseen and therefore unplanned, but necessary activities needed for the solution of non-conformities (failures, defects, malfunctions) that emerged during the aircraft inspection phases or during other maintenance activities. The former are activities, for which a precise processing schedule is defined by the aircraft manufacturer, they are predictable in nature and can be planned in advance; the latter, instead, are unpredictable and, in general, require the planning of unforeseen activities, defined through a process of technical evaluation of the problem encountered, which can have a significant impact on

work planning indeed. Depending on the age of the aircraft and the type of maintenance intervention, non-routines can constitute a significant portion of the entire workload, in literature up to 50% of total workload [3]. The experience of the planners plays an essential role in the planning of the activities, with the help of the company ERP and various other software tools.

The availability of an automatic or semi-automatic system to plan in advance and reliably the various activities necessary to complete a maintenance job emerges as a factor capable of offering a decisive competitive advantage for a company operating in the aircraft MRO sector. Such a system could allow a reduction in aircraft down-time, to the benefit of the flight operator who owns the aircraft, and lead to a more efficient use of resources with the consequent reduction of costs.

To support the operations of an MRO, the problem of planning the activities needed to complete an aircraft maintenance work order can be studied from the point of view of operational research (i.e., as a scheduling problem), or from a data-driven point of view for the prediction of workloads, made random by the occurrence of non-routines. The problem of planning tasks in a maintenance work order can be framed in the context of operational research as a Resource Constrained Project Scheduling Problem (RCPSPP) [4]. This is a well-known and NP-hard combinatorial optimization problem, usually solved using heuristic or meta-heuristic techniques such as genetic algorithms. In addition to the computational complexity of the problem, a further difficulty is given by the need to have a graph that describes the precedence relationships between all the activities to be planned, an information that is not generally available. The approach we use in this paper is that of data-driven capacity management [5], to support an MRO company in the strategic phase of quoting new work orders and allocating the resources necessary to complete maintenance tasks, taking into account the uncertainty due to non-routines [6], [7].

Being able to reliably predict actual workloads and future needs for spare parts and materials could represent a possible competitive advantage for a company operating in the aircraft maintenance sector. These problems can be effectively addressed by making use of data-driven analysis techniques based on statistics, data mining and machine learning. In fact, during its activity, an MRO collects a large amount of data on the work carried out, such as the type and model of aircraft, the number of flight hours/flight cycles of the aircraft at the time the order was started, the number of non-routines encountered, the number of actual work hours used to carry out the various tasks, components and spare parts requirements. This data, collected in the company's ERP, can be analyzed to be translated into information useful for planning activities, scheduling spare parts orders and also simulating possible workloads for future work orders. Based on the analysis of the maintenance projects data collected at an Italian aircraft MRO, we show that a large part of the maintenance tasks is due to the non-routines and that the amount of work for solving unexpected problems grows steadily as the age of the aircraft. We analyse the available data in a 4D frame of reference defined by maintenance check type, space (i.e., the aircraft work area where maintenance is carried out), time (i.e., the work phase when the maintenance is carried out), and skill (i.e., the certified technician needed to perform the maintenance activity) [8], [9].

3.2 Dataset

The data used in this work were made available by Atitech, an Italian aeronautical maintenance company that has been operating in the sector of MRO for many in years. The supplied data collects information relating a number of maintenance interventions on passenger class civil aircraft carried out in the period 2012-2019, on various Airbus A319 and A320 type aircraft.

The data were provided in the form of 34 files in CSV (Comma-Separated Values) format, in particular:

- No. 1 file contains all the information to identify the aircraft with the number of flight hours/cycles and the type of maintenance check carried out.
- No. 33 files contain the list of tasks carried out in the corresponding work order, with the indication of numerous information including: the area of the aircraft involved, the type of expertise of the workforce employed, the processing phase, the estimated and the reported man-hours needed to complete the single task, the type of task between scheduled or unscheduled. In total, there are 42 columns of data in each file.

In summary, the first set of data provided concerns: 33 maintenance events, 20 of the I2C type and 13 of the ILO type, 19 different aircrafts, and about 50,000 individual maintenance tasks. Atitech uses the labels I2C and ILO to denote two maintenance interventions belonging to the class of work type indicated in the aircraft maintenance manuals as check "C". These are in-depth checks of the individual systems and subsystems of the aircraft, requiring a thorough visual inspection of areas and components, as well as operational and/or functional checks. I2C checks are carried out every 48 months or in any case every 15,000 flight hours, ILO checks, which involve a greater number of scheduled activities than I2C checks, are scheduled every 72 months or every 22,000 flight hours.

3.3 Data preparation

The 33 files with the maintenance activities have been concatenated into a single file, of the 42 variables collected the less significant with respect to the project objectives have been eliminated, while a new field called WorkType has been added to keep track of the type of maintenance intervention carried out, as there is a notable difference in terms of overall workload between I2C and ILO checks. The variables selected for the following analysis are reported in Table 1.

Name	Description
WorkZone	The aircraft zone where the maintenance task has to be performed, as defined according the aircraft industry standard established by ATA [15].
WorkArea	The aircraft is logically divided into work areas and each area can contain multiple zones of the aircraft.
OrderNo	Label identifying uniquely the work order.
Description	Textual description of the maintenance task.
TaskText	Additional textual information about the task.
DefectType	Task type between scheduled/unscheduled.
Trade	Operator expertise requested to perform the task.
TaskCode	Work phase.
EstManHours	Estimated man hours to complete the task.
ActualHours	Reported man hours actually needed to complete the task.
WorkType	Type of maintenance check.

Table 1 – Variables in the dataset used in the analysis.

WorkPhase
PRELIMINARY
CLEANING
WASHING
OPENING
REMOVING
INSPECTION
OVERHAUL
MODIFICATION
SPECIAL WORK REQUIREMENT
REPAIR
LUBRICATION
SERVICING
PAINTING
INSTALLATION
CLOSING
TESTING
CHECK

Table 2 – Defined work phases, time ordered.

The analysis of the dataset highlighted the presence of a high number of empty cells, in some cases reaching percentages over 70%, most affected variables are in bold in Table 1. To reduce the number of empty cells, we proceeded with subsequent refinements, by analyzing the content of the variables **Description** and **TaskText**, it was possible to assign a plausible value to most if not all of the empty cells in the columns **WorkZone**, **WorkArea**, **DefectType** and **TaskCode**. Unfortunately, even after this data imputation phase, some work orders still had a high number of null fields and for this reason they could not be used in the subsequent analyzes and were therefore discarded.

The dataset contains one column, TaskCode, which classifies the maintenance task into 19 categories. Using these categories, it is possible to divide the maintenance process into a certain number of phases, ordered over time. This variable was translated into a new WorkPhase field to track the time phase of the activity, with the values, temporally ordered by domain experts, shown in Table 2.

At the conclusion of this data preparation activity, a dataset was defined to be used in the subsequent analysis phases. The dataset contains over 40,000 individual maintenance activities, relating to 24 work orders, of which 11 I2C-type checks and 13 ILO-type checks, as shown in the Table 3.

Two new check categories have been added: nl2C for aircraft performing an I2C check with more than 18,000 flight hours and nlILO for ILO-maintained aircraft with more than 42,000 flight hours. These maintenance interventions, in fact, can be considered higher order checks with particular characteristics and requirements.

Work order	Aircraft model	Check	Flight hours	Flight cycles
000257	A319	I2C	8,548	7,857
000267	A319	I2C	8,824	7,929
000276	A319	I2C	8,589	7,847
000281	A319	I2C	8,762	8,132
000290	A319	I2C	8,455	7,954
000299	A320	ILO	14,167	10,363
000306	A320	ILO	14,323	10,629
000307	A320	ILO	14,526	10,702
000313	A320	ILO	14,317	10,522
000319	A320	ILO	14,403	10,598
000331	A320	ILO	14,133	10,236
000362	A320	ILO	12,324	9,181
000365	A319	I2C	9,017	8,339
000366	A319	I2C	9,000	8,342
000403	A320	ILO	15,190	10,927
000408	A319	I2C	9,074	8,510
000448	A320	nl2C	19,301	14,406
000450	A320	nl2C	19,563	14,557
000467	A319	ILO	13,417	12,423
000468	A319	ILO	13,244	12,360
000472	A320	nl2C	18,273	13,812
000483	A319	ILO	13,559	12,673
000491	A320	nlILO	45,422	28,642
000492	A320	nlILO	42,017	27,712

Table 3 – Summary of the composition of the dataset.

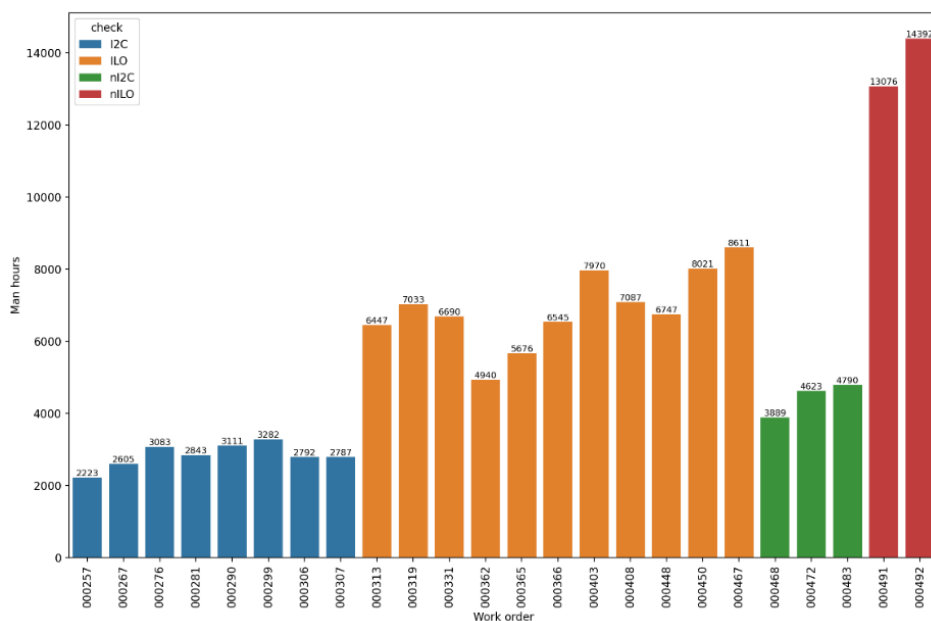


Figure 2 – Total number of man hours needed to complete a work order.

3.4 Data analysis

Once the maintenance activities dataset was organized, the data were analyzed with visualization techniques to better understand their structure and highlight interesting relations among the variables.

Figure 2 shows a bar graph of the total number of man hours required to complete each maintenance job in the dataset. As can be seen, confirming what was expected, on average the workload to complete an I2C type control is the lowest of all types of control. On average, an I2C check takes approximately 2,840 hours of work to complete, an nI2C check takes approximately 4,400 hours, an ILO check takes approximately 6,900 hours, and an nILO check takes approximately 13,700 hours. Of certain interest is to evaluate the impact of unscheduled work on the total hours needed to complete a maintenance check.

The graphs in Figure 3 clearly show how the impact of non-routines increases, especially in terms of workload, going from an I2C type check to an nI2C, ILO and nILO type check.

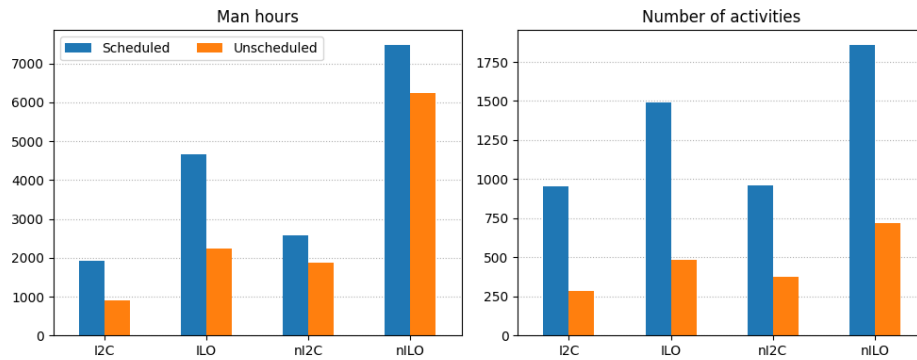


Figure 3 – On the left, the average number of man hours required to complete a maintenance check, divided between scheduled and unscheduled activities; on the right the average number of maintenance activities, again divided between scheduled and unscheduled.

In Figure 4 it is possible to see a bar graph with the number of non-routines found in the different areas of the aircraft for each type of check, while in Figure 5 a similar graph is shown with the average number of man hours necessary to resolve these non-conformities. In general, it is clear how the number of non-routines and the workload to solve them increase for each area as the complexity of the maintenance intervention increases. The areas most affected by non-routine interventions are the engines, the fuselage, the passenger cabin and the wings. The increase in non-conformities depending on the type of control is largely expected, both because the heavier ILO-type controls require a greater number of inspections and checks compared to I2C controls, and due to the inevitable greater wear and tear due of the use of the aircraft between checks.

Figure 6 shows several scatter plots of both the average number of man-hours necessary to complete a work order and the average total number of activities to be carried out, depending on the number of flight hours, the number of flight cycles and of the number of flight hours per cycle (ratio between the total number of flight hours and the number of flight cycles).

With respect to the number of hours and flight cycles, the points are distributed within vertical bands with respect to the type of check. This is an expected result, in fact, aircraft maintenance manuals precisely prescribe after how many hours/flight cycles (or months of use) the aircraft must undergo a certain type of check.

As can be seen, in the graph with the number of flight hours per cycle, the points are perfectly separated with respect to the aircraft model. This result probably depends on the strategic choices of the airline, which prefers to use the Airbus A320s, which have larger dimensions and load capacity than the A319s, on longer routes on average.

Following the work of Dinis et al. [8], the available data can be analysed to construct a 4D workload tensor with indices the check type c , the area of the aircraft a , the working phase p and the skill of the maintenance operator s . Each entry of this tensor, W_{caps} , gives the mean number of man hours requested for an operator with skill s , during the phase p , in the area a of the aircraft, in a check of type c . This information is of great importance not only in the quotation phase for the acquisition of

a new order, but also during the strategic phase of planning the tasks for a new maintenance work order. Summing over one of the indices, the information in the workload tensor can be nicely represented as a 2D heatmap.

In Figure 7, the heatmaps show the mean man-hour effort needed for aircraft maintenance with respect to the work phase and the aircraft area. These graphs give immediate visual feedback to the MRO planning department to where and when to expect the peaks in workforce demand during a maintenance workorder.

Similar charts can be obtained also with respect to the work phase and the requested skills, as shown in the Figure 8.

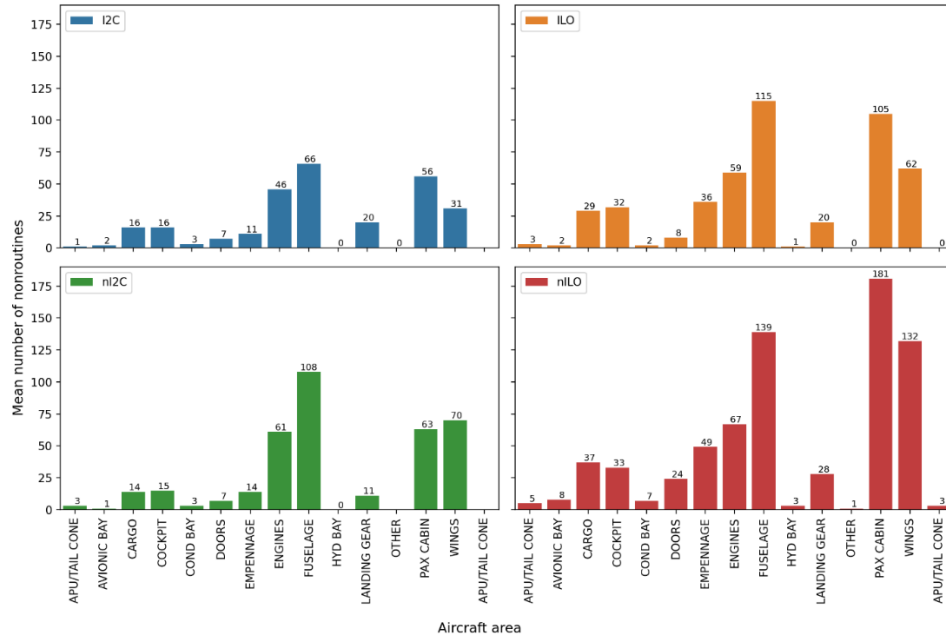


Figure 4 – Mean number of non-routines by aircraft area and check type.

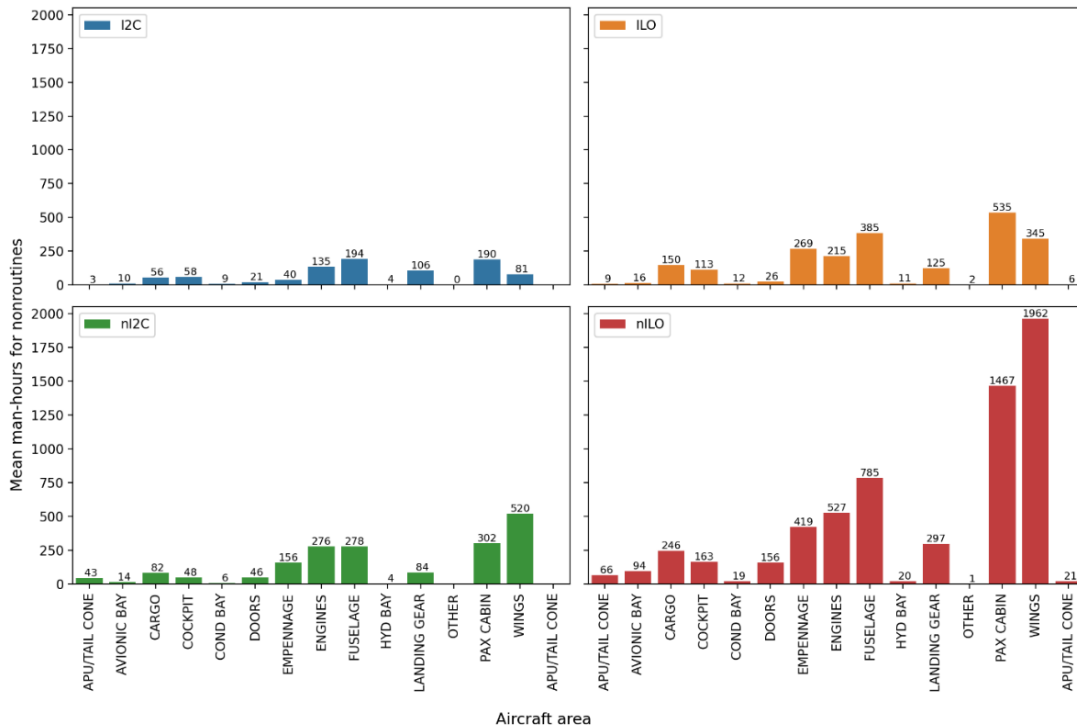


Figure 5 – Mean number of man hours needed to solve non-routines by aircraft area and check type.

4. Blockchain – MRO integration

4.1 Introducing Blockchain support

Another fundamental pillar of the proposed solution is the integration with the Blockchain to automate the notarization process of the successful execution of events in the certified maintenance process. We chose to use Blockchains [10] based on a Proof of Stake [22] consensus algorithm which do not significantly impact in terms of processing times. In fact, the use of a blockchain is advantageous in all those areas where the immutability of information and transparency are to be guaranteed. In the MRO sector, the use of Blockchain allows the creation of a secure and immutable system for the management and reporting of maintenance activities such as transactions that take place between operators and maintenance technicians, guaranteeing compliance with regulations in the form of validation rules transactions, adding further levels of security for the processing of information relating to the process.

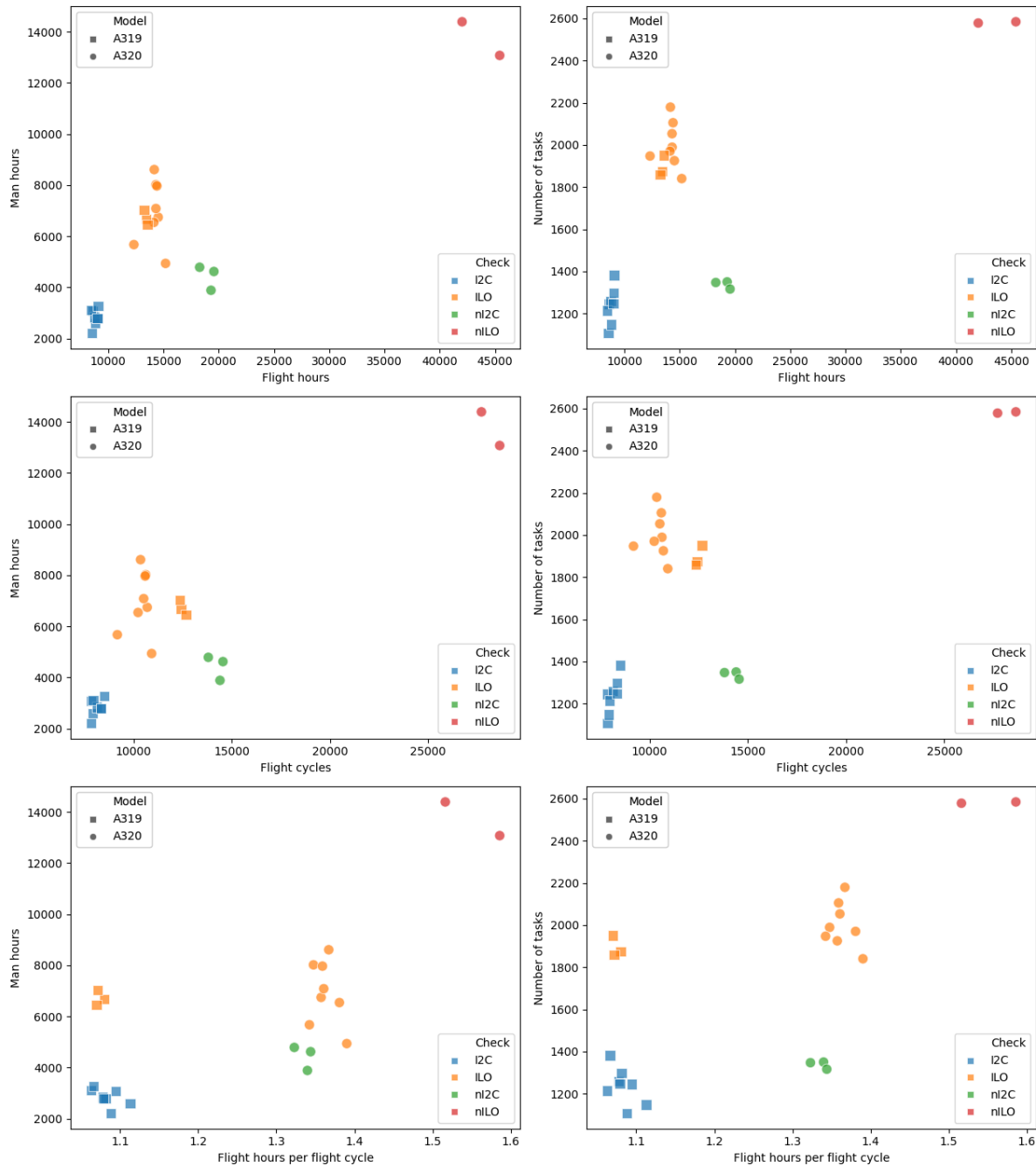


Figure 6 – Scatter plots of duration in man hours (on the left) and total number of tasks (on the right) with respect to flight hours (top), flight cycles (middle), flight hours per cycle (bottom), for all work order in the dataset.

In the current MRO maintenance process, the individual activities are expected to be carried out within four well-defined phases, which must be carried out in a defined order according to the international ENAC regulation. In each phase, the execution of each activity must be confirmed by three operators (OPM, OPV, OPA), the first who physically carries it out, a second who validates its correct execution and a third operator who approves it. Confirmation of each operator in charge occurs with the physical affixing of stamps provided and associated with the operators' details. In Figure 9 we represent interactions between users and technological components.

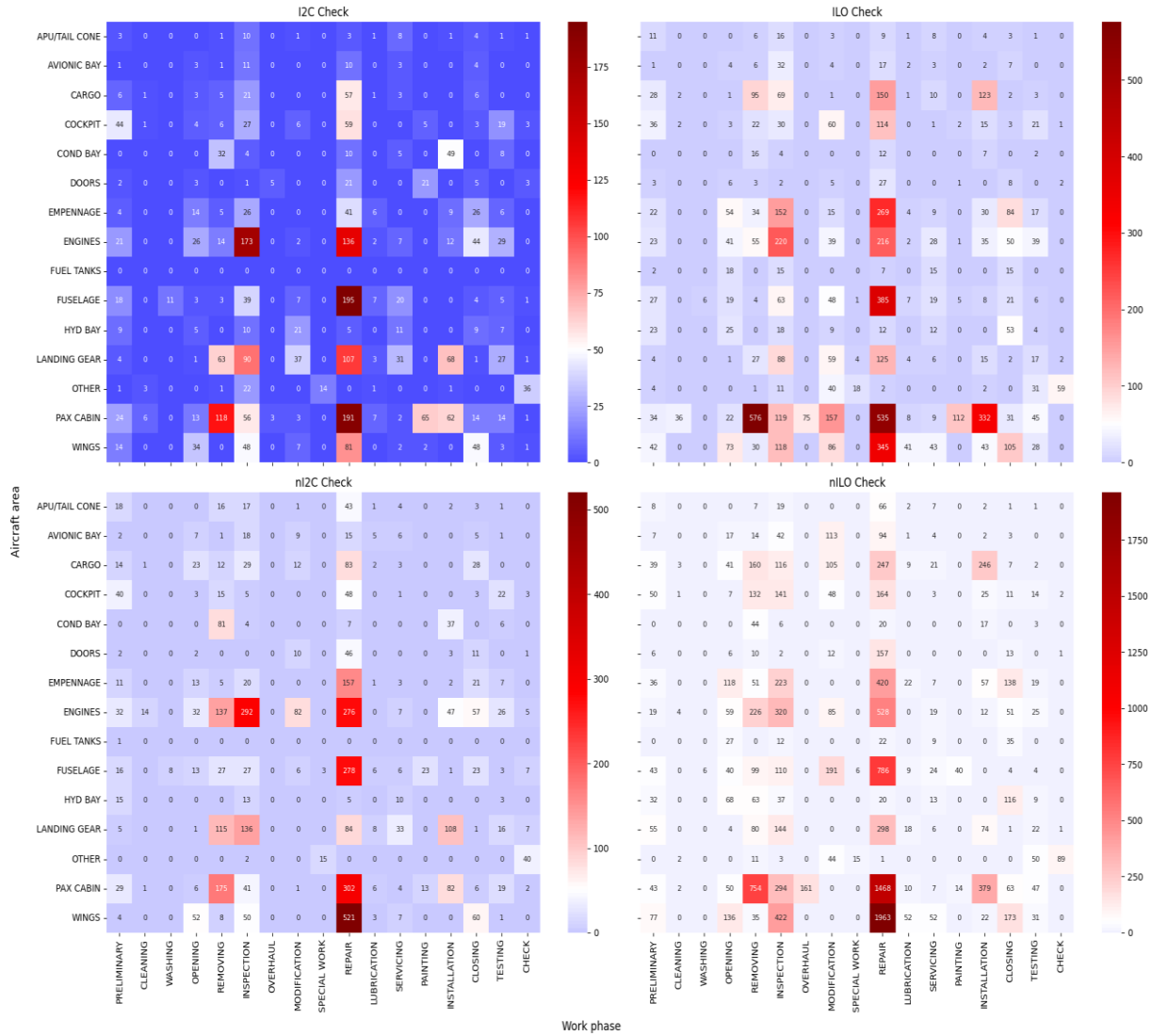


Figure 7 – Mean man-hour effort for aircraft maintenance in the work phase/aircraft area dimensions for each of the check type in the dataset.

4.2 Digitalization for the certification process with Blockchain

In a traditional notarization context, confirmation of the correctness of the execution is entrusted to a centralized guarantor authority. In this case, in the absence of an automated process, the time required depends on the applications of the regulations foreseen and defined by the authority.

In the specific MRO context, at the end of each phase a summary document of the activities carried out (WORK ORDER) must be produced, in PDF format which contains all the confirmation stamps placed by the operators. This document must be endorsed by a fourth certifying operator in charge who takes on the role of a notary.

The certified standard provides that if an operator does not confirm the correct performance of an activity, this must be re-performed by the previous operator, invalidating the confirmation he placed. In the context of research and development, the maintenance process has been computerized using a procedural manager that redefines the process by modeling the different phases with executive

steps and checking their correct sequential execution. Each step is activated only upon completion of the previous step, which results in the completion and complete confirmation at three levels of all related subtasks.

The processing sheets currently in paper format have been digitized and managed with a mobile app specifically developed with Flutter technology. The registration of the execution of an activity validated by affixing physical stamps on paper has been replaced with the blockchain registration of confirmation of execution of the activity via mobile app.

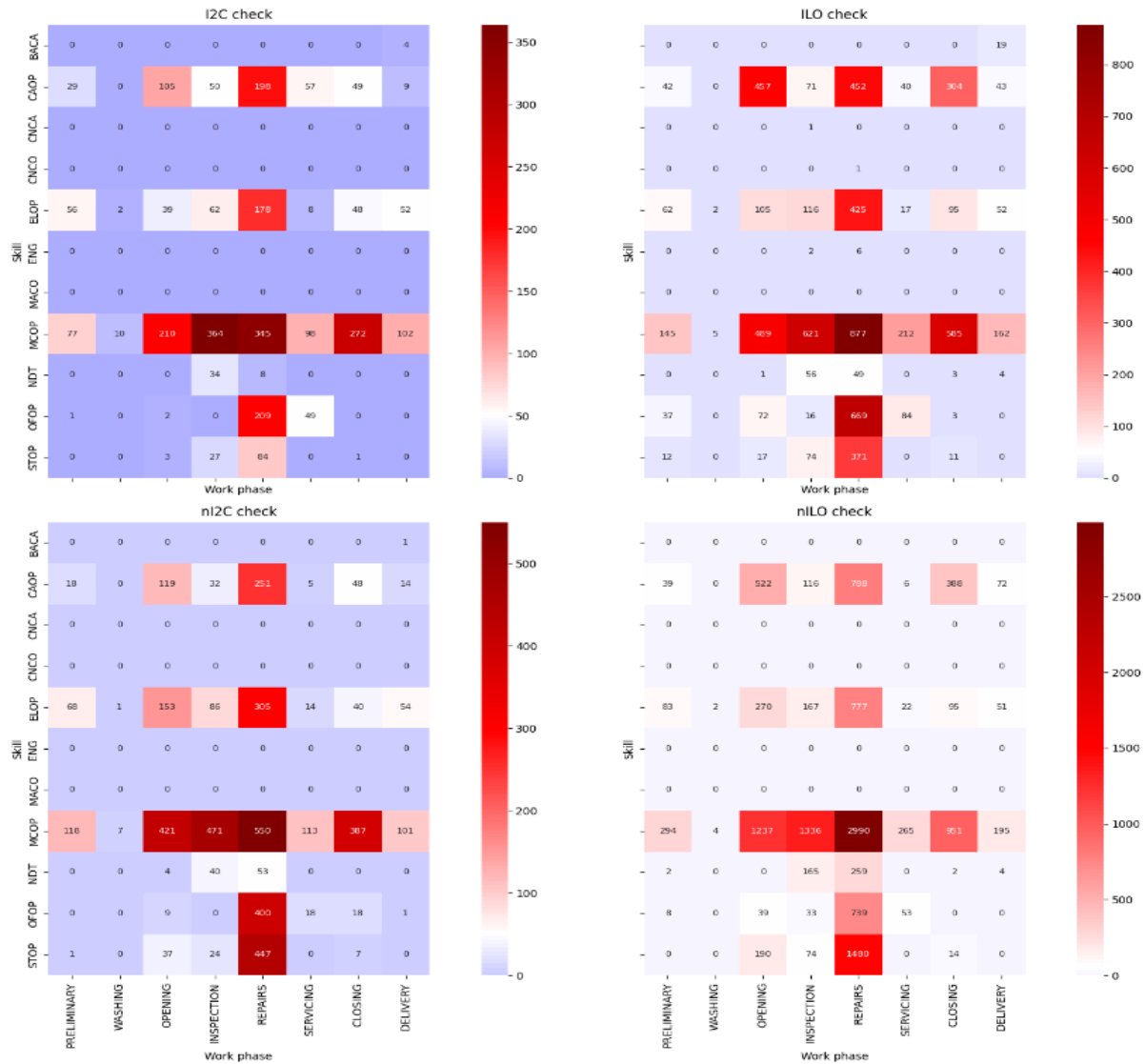


Figure 8 – Same as Figure 7, but in the work phase/operator skill dimensions.

The overall computerization of the process leads to significant savings in terms of time and management costs compared to the use of paper supports alone and the required intervention of a centralized external authorized certifying body. The management of complete data relating to a maintenance process, which for policy reasons cannot be distributed in a public register, is entrusted to the procedural manager who inserts them appropriately and automatically into his database. The blockchain is used to support the procedural platform, in order to speed up the notarization aspect and make the related information immediately available, recording some events in its register. Specifically, regarding operations:

- Start of the maintenance process: the name of the process instance, the successful start, and the number of scheduled ordinary activities of the process are recorded in the Blockchain.
- Confirmation/non-confirmation of activity: the affixing (timestamp) of each confirmation (stamp) or non-confirmation (reject) by the operators in charge. The enabled roles all have access to

an Algorand multi-signature wallet, which allows multiple operators to be authorized to submit the same block, relating to processing, to the Blockchain.

- Completion of a maintenance phase: at the end of each phase, a PDF document summarizing the activities carried out and confirmed is generated. This document is generated and downloaded from the platform, digitally signed by the certifying operator and reloaded into the platform.
- Closing of the maintenance process: following the correct completion of the maintenance phases, the name of the process instance, the successful closure, and the number of ordinary activities carried out are recorded in the blockchain.

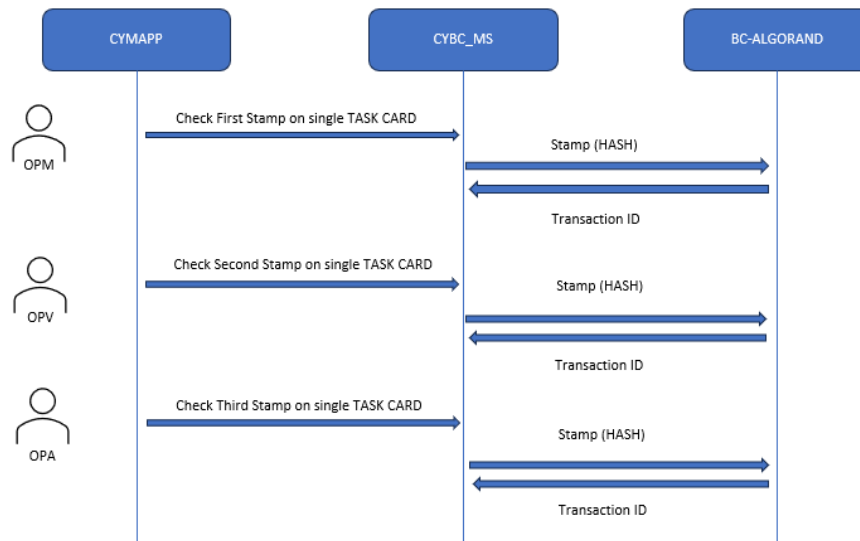


Figure 9 – Interaction of technological components for the digitalization of the certification process associated with a maintenance flow.

The birth of Blockchain technology has made it possible to streamline the document notarization process by making an accessible platform available to interlocutors, but which guarantees immutability and the guarantee of data preservation considering the use of the redundancy of the same within the nodes which constitute its structure. The evolution of this technology has made it possible to reduce the times and costs associated with processing transactions, making it a valid alternative to current centralized and non-automated solutions. In the ongoing experimentation, the “Algorand” Blockchain [23] was chosen, whose use of the Proof of Stake consensus algorithm, distributed across all the nodes of the register, determines performance in terms of execution times in line with a workflow context procedural, without determining excessive and unexpected delays due to the variable approval times of a block as happens with first generation blockchains.

The integration of the Blockchain was achieved by implementing a microservice with .Net Core technology, integrated with the Algorand SDK and which is called by the procedural manager for the recording of events/data in the blockchain, and which takes care of the construction of the block to be submitted for approval of the blockchain. When a block sent to the blockchain is approved and inserted into the chain, the register returns the code of the transaction in which it was inserted and this constitutes a registration confirmation receipt. The story received is stored in the microservice database together with the identifier of the step from which the recording was activated. The microservice communicates to the platform the receipt of the received bill, and it in turn automatically sends a notification to the operator, which can be viewed from the specially developed mobile app. Furthermore, the microservice also allows you to verify the originality of the document produced in an end-of-activity step, comparing its HASH coding with that recorded in the block relating to the transaction receipt associated with the step. In the first implementation of the system, the security of the platform provides access via credentials (operator registration number and password) and the association of an Algorand account, in the dedicated microservice, for operators authorized to

interact with it via the platform.

At the end of each phase for the maintenance process, a summary document, called WORK ORDER, of the activities carried out is produced in the CYMA platform, it is possible to register one or more versions of the same in the blockchain. The WORK ORDER documents contain the confirmation stamps placed by the operators. This functionality is enabled only for certifying users. After receiving the transaction ID, following the data registration in the blockchain, the CYBC microservice sends a signal to the CYMA platform to disable further modification and deletion of the corresponding notarized documents [Figure 10].

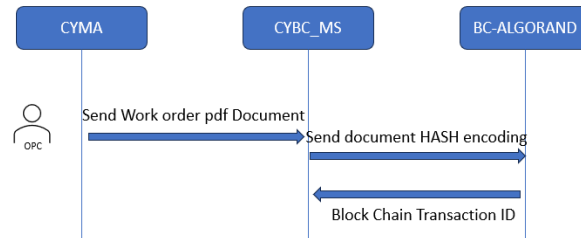


Figure 10 – Interaction between technological components work order documents notarization.

In the CYMA platform, in the process steps dedicated to the management of work orders of each phase, it is possible to verify the authenticity of a PDF document relating to a massive work order. The enabled user can upload a PDF file and verify that this file corresponds to the original version recorded in the blockchain [Figure 11].

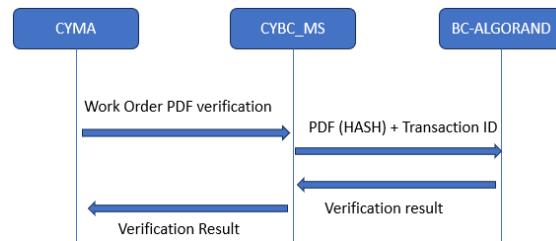


Figure 11 – Interaction between technological components for work order pdf document authenticity verification

5. Asset tracking

5.1 Introduction

The possibility of collecting real-time information on the position and movement of company equipment is a fundamental tool for improving knowledge of internal systems and processes. This technology enables companies to enhance business processes, optimize execution times, and monitor activity status.

For example, knowing the location of an object in advance reduces retrieval time from a warehouse or workshop. Real-time feedback on the movement of components also optimizes maintenance processes. All data collected through asset tracking can be recorded to create a database that, using Data Analytics tools, can be analyzed for planning and optimizing processes.

One critical aspect of tracking industrial or corporate assets is choosing the most appropriate technology. Various applicable technologies exist, each with unique characteristics, strengths, weaknesses, and installation constraints.

Once the association between the physical element to be tracked and its digital identity is established, the tracking information can feed management systems or systems that supervise specific processes, creating a link between the physical and digital worlds. The choice of technology determines important characteristics of asset tracking, such as location precision, update frequency, type of location (indoor or outdoor), and solution cost, particularly the tag to be applied to the asset. Based on a study of tracking systems used in various application fields, a system based on Bluetooth Low Energy (BLE) was selected. This system monitors the position of a target, activated by

movement, affixed to the disembarked parts. A server records the movements for analysis.

BLE, the low-power version of Bluetooth developed for the Internet of Things (IoT), uses the unlicensed 2.4 GHz radio band to interconnect nearby devices. Bluetooth is a widespread technology in interior spaces and is supported by many devices today. Released in 2010, BLE 4.0 consumes significantly less power than Bluetooth Classic and other RF standards. This energy-efficient design has fostered the development of wearables, IoT devices, and battery-powered BLE beacons. The two major beacon protocols, Apple's iBeacon and Eddystone, along with other BLE technologies such as location sensors and tags, have enabled a wide range of indoor location and positioning service applications.

Continuous advancements in BLE technology aim to reduce consumption, interference, increase interoperability, and improve accuracy in position measurement. BLE beacons are small, low-power Bluetooth transmitters detectable by wireless devices like BLE-enabled smartphones. Beacons can be installed in fixed locations or placed on mobile assets to provide location references for indoor positioning applications. They can be used to locate a device, deliver relevant content, or offer time or location information, keeping users informed and engaged.

Beacons transmit signals at regular intervals that can be detected by other BLE-enabled devices. Beacon location data is collected from a BLE device and forwarded to a server to determine the device's location. This can support various location-sensitive applications and even trigger specific actions. Beacons come in all shapes and sizes. BLE technology is typically cheaper to produce than other RF technologies, resulting in small, low-cost, low-maintenance hardware options that can be customized for implementations that meet specific needs. Some beacons BLE incorporate additional technologies such as accelerometers or temperature sensors for better results.

5.2 How BLE positioning works

BLE indoor positioning solutions use BLE-enabled sensors to detect and locate transmitting Bluetooth devices, such as beacons or tracking tags in indoor spaces. Location data collected by sensors or sent by beacons are then captured by various location applications and translated into information for specific application use.

5.3 BLE positioning with sensors

BLE positioning with sensors uses BLE-enabled sensors that are deployed at fixed locations in an indoor space. These sensors passively detect and locate transmissions from BLE asset tracking tags, beacons, personnel badges, wearables and other Bluetooth devices based on the signal strength received from the transmitting device. The distance of the tag is started through the measurement by the receiving devices of the RSSI (Received Signal Strength Indicator), i.e. the power with which the signal is received from the tag.

This location data is then sent to the indoor server where a localization engine analyzes the data and uses algorithms to determine the position of the device transmitting the RSSI measurements received from the beacon. These coordinates can be used to display the location of a device or asset on an internal map of the monitored space

Each object or person to be tracked is equipped with a specialized battery-powered BLE tag that transmits its unique ID at pre-set intervals via radio frequency.

The tags periodically transmit a message which is collected by special devices appropriately located in the area to be monitored and which are able to reconstruct what is called "proximity localization", i.e. the association with the tag (and therefore with the asset) of the position relative to the area closest to the tag in question. The precision is therefore that of the so-called area, which can be for example a room, a portion of a larger hall, or a corridor, or a warehouse.

Tagged assets are detected by strategically placed BLE anchors. Locations are calculated based on advanced algorithms with an accuracy of up to 3m depending on the density of the infrastructure. Real-time location information is sent to the central database which can be accessed on a map or list view using an intuitive user interface

5.4 How accurate is Bluetooth positioning

BLE indoor positioning and real-time tracking systems can produce different levels of accuracy depending on the system architecture, hardware selections, and the density of installed sensors or

beacons. Both indoor positioning and the use of BLE sensors or beacons can provide location accuracy typically less than 5 meters (with optimal conditions and implementation).

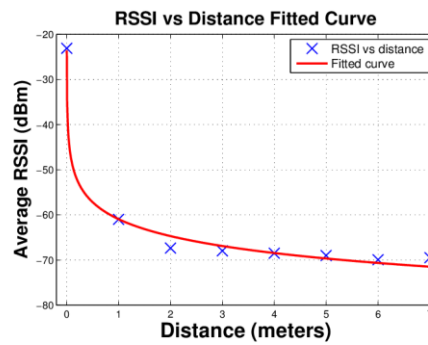


Figure 12 – Typical RSSI vs distance curve.

Bluetooth, similar to Wi-Fi technologies, typically relies on signal strength (RSSI) to estimate the location of devices [Figure 12]. This method of determining position typically provides meter-level positional accuracy. While BLE is not currently the most accurate RF technology for indoor positioning, it is still highly effective and one of the most widely used. Many indoor positioning use cases do not require a high degree of accuracy, making BLE a suitable option that offers many unique benefits including flexibility, low power and cost, and ease of deployment.

The BLE positioning range may vary depending on factors such as the use of BLE beacons or BLE-enabled sensors or the nature of the indoor space. BLE generally operates over a shorter range than other RF technologies, such as UWB or Wi-Fi, working best within 0-25 meters and up to 100 meters (with optimal conditions and deployment).

5.5 Location detection

The protocol on which BLE is based uses advertisement packets through which a device can provide additional information to other devices involved in the architecture. In these packages, we find the presence of a unique identifier for each device called UID number which can be read by different Bluetooth receivers. Once a device receives the signal, it can activate the localization process. The frequencies used for data transmission over BLE are such that radio waves can penetrate even physical barriers. It is clear that when a device sends the advertisement packet, the devices interested in localization must be set up to receive it or must have Bluetooth activated.

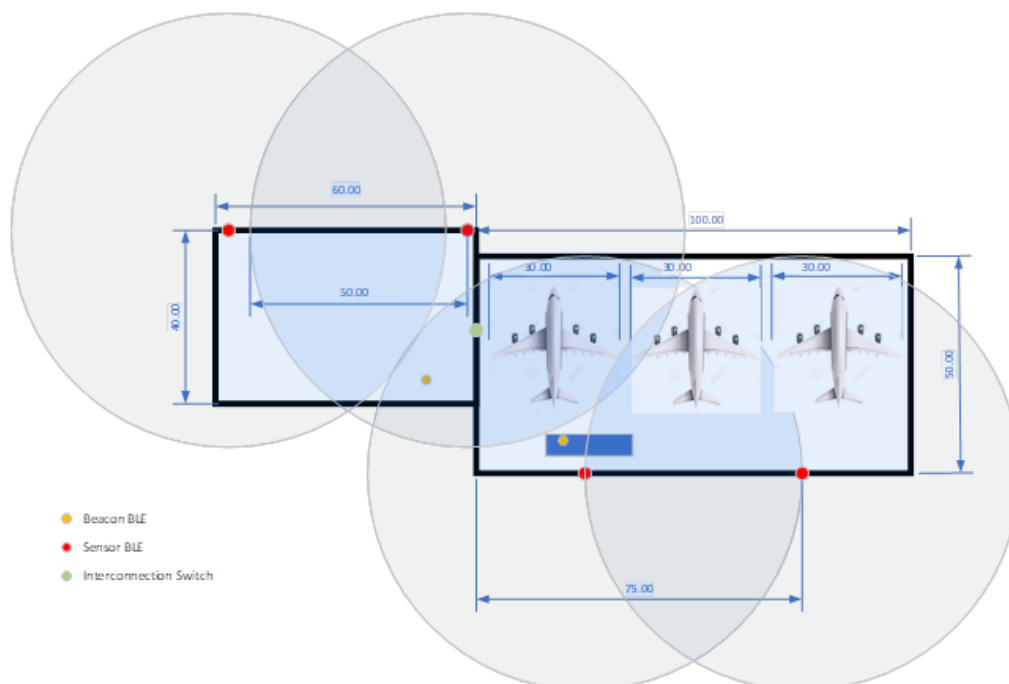


Figure 13 – Layout of the BLE sensors and beacons

5.6 Physical architecture

In the current application, we have tried to use a minimum number of sensors to identify the position of the BLE Beacon assigned to the landed asset.

Taking advantage of the geometry of the rooms to be monitored, only 2 BLE sensors were positioned on one side of the room to be monitored, eliminating the ambiguity of triangulation with only 2 sensors by excluding solutions that are located outside the room to be monitored [17], [21].

The Figure 13 shows the layout of the BLE sensors and beacons used in our application, the distances shown are expressed in meters.

In Figure 14, the 2 sensors positioned at a distance D_s from each other measure the RSSI of the beacons installed on the landed components and send it to a UDP server.

In this application, it was possible to use only 2 sensors, because it is possible to logically discard the solution that would lead to identifying the Beacon outside the monitored area because this solution is not acceptable.

For each beacon, the server calculates the distance d_1 and d_2 from the sensors through a previously constructed RSSI vs Distance calibration curve. The calibration curve ([16]-[20]) has the equation:

$$RSSI = K_0 - 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right)$$

where d_0 is the reference distance for a RSSI of K_0 .

The propagation constant n depends on the environment where the signal is transmitted, the K_0 constant is evaluated precisely by the manufacturer at the distance of 1 meter (then the first part of the sum equals zero) and it is hardcoded into each device [19].

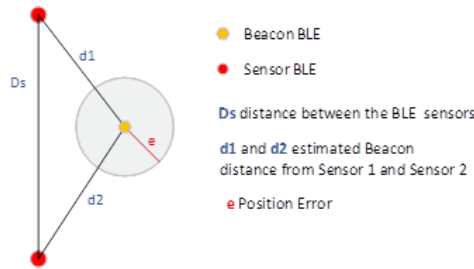


Figure 14 – Beacon distance estimation.

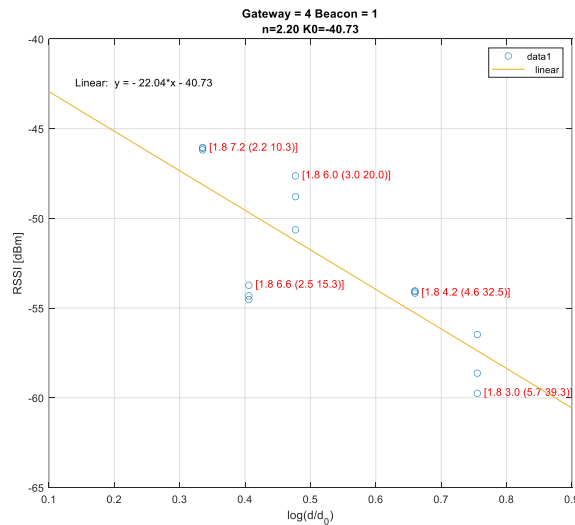


Figure 15 – Typical calibration curve.

In this application, the parameters K_0 and n of the calibration curve have been calculated with measurement in known positions of the beacons to the sensors. In Figure 15, the calibration curve

relevant to a specific used beacon is illustrated where the output coefficients are $K_0 = -42.73 \text{ dBm}$ and $n = 2.204$. From preliminary tests, the positioning error is less than 2.5 meters. However, at the time of writing this paper, there are other ongoing studies to evaluate other specific algorithms that could improve the position error.

6. Conclusion and future work

The objective of this work is the definition and implementation of a set of enabling technologies that can allow a company operating in the aircraft maintenance sector to improve the efficiency of its production processes, reducing processing times and costs. The project fits naturally within the digital transformation process promoted by the European Industry 4.0 initiative. A crucial problem to address consists in promoting innovation within a workflow consolidated over years of activity and with peculiar characteristics, determined by the need to conduct aircraft maintenance operations while maintaining high levels of transparency and traceability in order to respect the rigorous requirements required by the flight security authorities. The maintenance of an aircraft, in fact, is a very complex activity that requires work programming and planning strategies, control of operations and specific skills, especially in consideration of the numerous activities to be carried out in the execution of a work order and the rigorous regulations to guarantee the necessary levels of reliability and safety. Three different lines of activity have been identified and developed: (1) using data relating to orders already completed to obtain information useful for estimating and planning new orders (capacity planning); (2) create a work document tracking system based on blockchain technology to ensure compliance with procedures and immutability of information; and (3) implement a tracking system for grounded components via a wireless infrastructure capable of detecting their location at any time.

The data provided by the partner aeronautical maintenance company, Atitech, was pre-processed to integrate missing information and eliminate unusable records, so it was possible to build a dataset suitable for the subsequent analyses. The small number of orders present in the dataset did not allow the construction of sophisticated forecasting models, however the exploratory statistical analysis still allowed us to obtain valuable information for planning new orders. In particular, the heat maps presented in this article provide immediate visual feedback to identify, for each type of maintenance intervention, in which processing phase the greatest use of manpower is required depending on the area of the aircraft involved and/or the specialization (skill) requested for the operator.

The analysis of the maintenance process and regulatory requirements allowed the development of a document flow management system based on blockchain technology. By using a Proof of Stake (PoS) consensus algorithm, the developed solution ensures that processing times does not significantly impact the carrying out of maintenance activities. Blockchain provides immutability and transparency, which is beneficial for managing and reporting maintenance activities in the Maintenance, Repair, and Overhaul (MRO) sector. It allows secure and immutable records of transactions between operators and technicians, ensuring regulatory compliance through validation rules.

The implementation of a real-time tracking system of the disembarked components reduces retrieval time, enhances maintenance processes, and allows data collection for analysis and process optimization. Choosing the appropriate tracking technology is crucial, as it affects location precision, update frequency, and costs. After evaluating various systems, Bluetooth Low Energy (BLE) was chosen for its low power consumption and widespread use in IoT applications. BLE uses the 2.4 GHz radio band and supports many devices, making it ideal for indoor tracking and positioning. BLE beacons, small low-power transmitters, provide accurate location data and can trigger specific actions. They are cost-effective, low-maintenance, and can be enhanced with additional sensors for improved results.

As future work, we plan to achieve a tighter integration in a unique system of the various parts developed and presented in this article. We will work on an expansion of the historical dataset of past maintenance work orders to gain insights into the cause of non-routines, and to develop workload models with predictive capacity, especially regarding the prediction of workload due to the unscheduled activities.

7. Contact Author Email Address

Francesco Martone, mailto: f.martone@cira.it

8. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third-party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

- [1] Kinnison H A. *Aviation Maintenance Management*. McGraw-Hill, 2012.
- [2] Rodrigues D, Lavorato P. Maintenance Repair and Overhaul (MRO) fundamentals and strategies: An aeronautical industry overview. *International Journal of Computer Applications*, vol. 135, No. 12, pp. 21-29, 2016.
- [3] Premaratne S, Senevi K. Aircraft maintenance planning and scheduling: an integrated framework. *Journal of Quality in Maintenance Engineering*, Vol. 18, No. 4, pp 432-453, 2012.
- [4] Neron E, Demasse S, Artigues C (eds.). *Resource-Constrained Project Scheduling: Models, Algorithms, Extensions and Applications*. Wiley-ISTE, 2013.
- [5] Duffuaa S, Alfares H. Methods and Approaches for Maintenance Capacity Planning. Proceedings of the International Conference on Industrial Engineering and Operations Management, Dubai, United Arab Emirates (UAE), pp. 1674-1677, 2015.
- [6] Dinis D, Barbosa-Póvoa A, Teixeira A P. Valuing data in aircraft maintenance through big data analytics: A probabilistic approach for capacity planning using Bayesian networks. *Computers & Industrial Engineering*, vol. 128, pp. 920-936, 2019.
- [7] Georgiev K, Vachev N. Predicting the unscheduled workload for an aircraft maintenance work package. Proceedings of the 13th International Scientific Conference on Aeronautics, Automotive and Railway Engineering and Technologies, Sozopol, Bulgaria, 2022.
- [8] Dinis D, Barbosa-Póvoa A P, Teixeira A P. A supporting framework for maintenance capacity planning and scheduling: Development and application in the aircraft MRO industry. *International Journal of Production Economics*, vol. 218, issue C, pp. 1-15, 2018.
- [9] Fabig C, Völker M, Schmidt T. Provision of Model Parameters for Capacity Planning of Aircraft Maintenance Projects: A Workload Estimation Method based on Enterprise Resource Planning Data. Proceedings of the 12th International Conference on Advances in System Simulation, Porto, Portugal, pp. 24-30, 2020.
- [10] Miller D. Blockchain and the Internet of Things in the Industrial Sector. *IEEE IT Professional*, vol. 20, no. 3, pp. 15–18, 2018.
- [11] Efthymiou M, McCarthy K, Markou C, O'Connell J F. An Exploratory Research on Blockchain in Aviation: The Case of Maintenance, Repair and Overhaul (MRO) Organizations. *Sustainability*, vol. 14, 2643, 2022.
- [12] Ho G T S, Tang Y, Tsang K, Tang V, Chau K. A blockchain-based system to enhance aircraft parts traceability and trackability for inventory management. *Expert Systems with Applications*, vol. 179, 115101, 2021.
- [13] Inayatulloh D L, Kusumastuti, Hartono I K. Aircraft Reliability and Maintenance with Blockchain Technology to Improve Flight Safety. Proceedings of the International Conference on Smart Computing, IoT and Machine Learning (SIML), Surakarta, Indonesia, pp. 156-160, 2024.
- [14] Andrei A G, Balasa R, Costea M L, Semenescu A. Building a blockchain for aviation maintenance records. *Journal of Physics: Conference Series*, vol. 1781, p. 012067, 2021.
- [15] ATA. ATA Specification 100 – Specification for Manufacturers' Technical Data. Revision No. 37, Air Transport Association of America Inc., 1999.
- [16] Ramirez R, Huang C-Y, Liao C-A, Lin P-T, Lin H-W, Liang S-H. A practice of BLE RSSI measurement for indoor positioning. *Sensors*, No. 15:5181, 2021.
- [17] Kaczmarek M, Ruminski J, Bujnowski A. Accuracy analysis of the RSSI BLE SensorTag signal for indoor localization purposes. 2016 Federated Conference on Computer Science and Information Systems (FedCSIS), Gdansk, Poland, pp. 1413-1416, 2016.
- [18] Guo Y, Zheng J, Zhu W, Xiang G, Di S. iBeacon Indoor Positioning Method Combined with Real-Time Anomaly Rate to Determine Weight Matrix. *Sensors*, No. 21(1):120, 2021.
- [19] Bembenik R, Falcmann K. BLE Indoor Positioning System Using RSSI-based Trilateration. *J. Wirel. Mob. Networks Ubiquitous Comput. Dependable Appl.*, Vol. 11, No. 3, pp. 50-69, 2020.
- [20] Zhu X, Feng Y. RSSI-based Algorithm for Indoor Localization. *Communications and Network*, Vol. 5, No. 2B, pp. 37-42, 2013.
- [21] Farooq-I-Azam M, Ni Q, Dong M. An Analytical Model of Trilateration Localization Error. 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, pp. 1-6, 2019.
- [22] Kogan L, Fanti G, Viswanath P. Economics of Proof-of-Stake Payment Systems. *MIT Sloan Research Paper* No. 5845-19, 2021.
- [23] Chen J, Micali S. Algorand: A secure and efficient distributed ledger. *Theoretical Computer Science*, vol. 777, pp. 155-183, 2019.