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## CRITICAL ROLE OF AIRCRAFT MAINTENANCE IN OPERATION: NOVEL SOLUTIONS FOR ENHANCED EFFICIENCY AND RELIABILITY

**Summary.** Today, aviation is a leading industry. The market is growing yearly, and the expectations required from supporting aviation sectors have spiked to keep up with the requirements of a dynamic and safety-demanding industry. This paper explores the critical role of aircraft maintenance in ensuring operational accuracy and effective project management within the aviation industry. Besides describing the impact of maintenance activities on efficiency, reliability, and readiness, this paper presents a new way of prioritizing the development of projects according to the structured roadmap; introduces a novel artificial intelligence-based methodology for accurately predicting the real tasks' man-hours depending on the archived previous data; and shows a model development for capacity and resource planning and scheduling for maintenance activities. A robust procedure is presented for increasing the technological level with the highest margin, improving resource allocation, minimizing aircraft downtime, and ultimately setting a new standard for efficiency and reliability in aircraft maintenance.

### 1. INTRODUCTION

The aviation industry operates at the highest level of safety, airworthiness, and reliability. These high standards form standard expectations of every sector that is included in or related directly or indirectly to the aviation industry. This means that all sub-sectors and service providers are obliged to provide the same quality of work and present the same level of efficiency. At the core of aviation is aircraft maintenance, a field that extends beyond the technical aspects of maintenance to reach the pillars of operational readiness and project management.

As expectations from the aviation market evolved, as a consequence of the natural economic growth [1], so did the mentality of the entire discipline. There has been a transition toward prioritizing performance, necessitating operational excellence. Consequently, maintenance, repair, and overhaul (MRO) businesses persist in pursuing more proactive and strategic advancements in asset management. Not only has this shift had positive effects on the safety and functionality of an MRO company, but it has also embedded the constant search for better developments and state-of-the-art investments to stay competitive and relevant in a demanding market.

This paper examines the delicate relationship between maintenance activities and operational efficiency. It highlights the need for modern data-based approaches to enhance workflow and optimize project management. Hence, in this research, first, a roadmap of item prioritization tasks has been outlined and solved, where factors like regulatory compliance, aircraft utilization, and risk assessment are considered. Additionally, the importance of integrating technology, particularly in scheduling and resource allocation, is investigated as a key enabler of enhanced efficiency. A robust Artificial Intelligence (AI) module was introduced that accurately calculates the time needed for the maintenance activities, together with the development of the Constraint Programming framework, with the main goal of minimizing downtime and maximizing resource utilization.

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Although there is a large amount of data available today, which is collected in electronic or printed format, this data is not used nearly as much as it could be. This is because the processes rely more on human involvement rather than digital solutions [2].

The higher workload and the slow development of the MRO industry have led to an unwanted increase in cost, time, and capacity, which originates from several areas, such as:

1. High material and energy consumption (due to printed documents and their infrastructure, for example).
2. Added risk of human errors.
3. Elevated labor/working hours required to manage and deliver work packages.
4. Intensified communications.
5. Reduced transparency of projects/tasks.
6. Reduced flexibility of working environment (e.g., the questions of open and home office).
7. The scheduling process and the distribution of capacity, cost, investment, inventory, tools, and workplaces are hard, inaccurate, and inefficient.
8. Not supporting the task-planning or backlog prioritization to be quicker, better optimized, and more frequent.

Based on the identified feature items of the operational process described above, the intensification of digitalization in the MRO processes decreases the overall cost, time, and capacity.

However, before starting the developments originated from the topic mentioned in the previous paragraph, it is worth investigating the priority of the different tasks to be addressed globally. Hence, the introduction of a new prioritization method for roadmap items is presented in the next chapter, and a new digital framework is developed and presented afterwards to improve the operational characteristics. In this context, *digitalization* refers to not just the transferring, managing, and storing of data but also leveraging this information to identify optimal planning and scheduling solutions through advanced optimization and AI theories.

## 2. STRUCTURED APPROACH TO PRIORITIZING MAINTENANCE DEVELOPMENTS

Aircraft maintenance plays a critical role in aircraft airworthiness and has a direct effect on the operational life of an aircraft. For airlines, the focus is always on their assets, which are their fleets. Many airlines have looked at maintenance as a liability since it makes the operators spend money rather than flying the aircraft and generating money. However, in past decades, this perspective has shifted; airlines are more accepting of maintenance and seek high-quality and efficient MRO enterprises [3] to extend the operational life of their most expensive asset.

Providing profitable maintenance services means reaching an optimized level of balance between cost, quality, and time. If the aviation industry continues to follow such a steep growth curve, the MRO sector will also have to adapt in order to remain competitive with other leading MRO companies and meet manufacturers' requirements.

A structured approach to prioritizing maintenance development is crucial for maximizing efficiency and minimizing risks. The proposed roadmap considers multiple factors, including regulatory requirements such as prioritizing some mandatory requirements and maintenance regulations as well as standards enforced by aviation authorities (e.g., FAA, EASA) [4]. These are non-negotiable and must be performed according to strict schedules [5].

Another potentially critical factor is the company's growth and its technological readiness because rapid growth often strains existing maintenance resources, demanding scalable solutions and efficient processes to keep pace with an expanding fleet and increased operational pace [6]. If maintenance practices remain static while the company grows, bottlenecks and delays are inevitable, which impact safety and operational efficiency. Furthermore, a company's technological readiness, which is its ability to adopt and integrate new technologies, plays a significant role in optimizing maintenance activities. Embracing advancements like predictive maintenance systems, digital documentation, and automated scheduling tools can significantly improve efficiency, reduce costs, and enhance decision-making. Conversely, a company that lags in technological adoption may struggle to compete and may face

increasing challenges in managing the complexity of modern aircraft maintenance. Therefore, aligning maintenance strategies with current growth and future technological capabilities is essential for sustained achievement in the aviation sector. The above-mentioned circumstances make it hard to process a technological MRO roadmap that paves the way to the MRO development milestones [7].

Analyzing the various research endeavors in this scientific area revealed common characteristics among the published studies, enabling the categorization of distinct topics (see Fig. 1). Many development ideas can be defined from this roadmap.

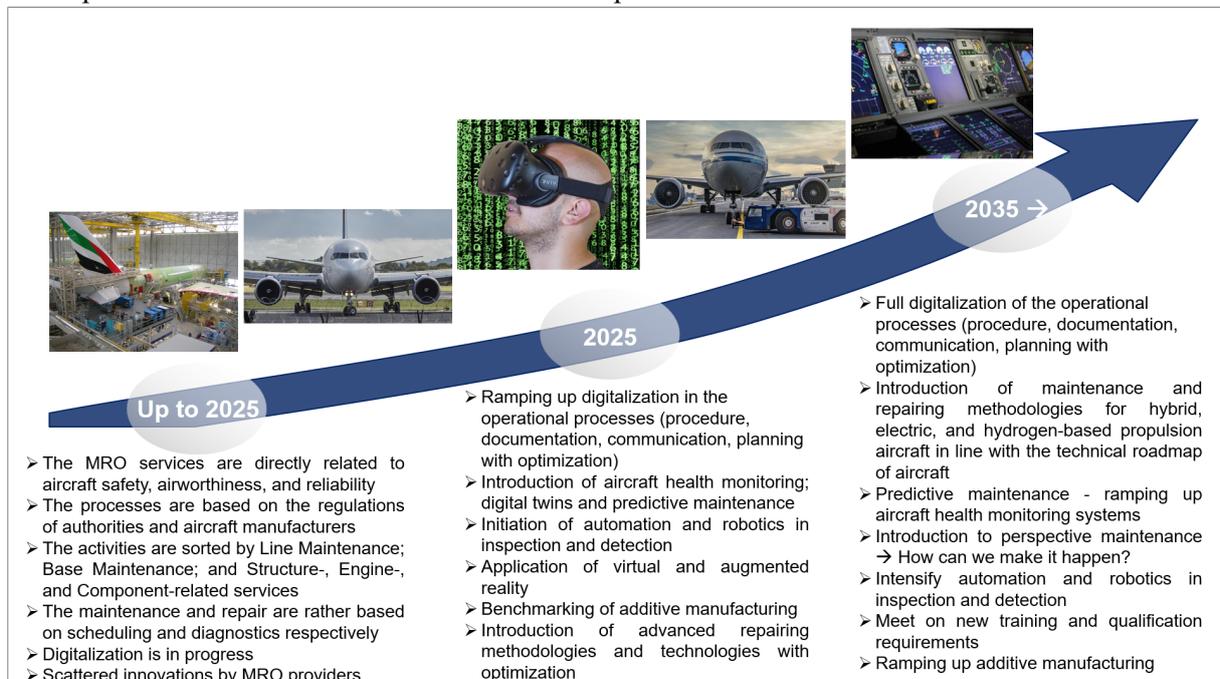


Fig. 1. Technological roadmap for MRO activities. (Created by the author)

It is essential to establish categories for the technological advancements to facilitate the process of making decisions for selecting the next development area of an MRO company [8]. Many research studies with different topics have been conducted in areas of interest; the subjects of investigation are classified into three primary categories in the present work:

1. Development of the operational methodology and planning.
2. Technology development for inspection and detection.
3. Technical developments in maintenance, repair, and overhaul.

A new set of assessments is established in order to determine the most important category. The following items are considered for the evaluation:

- 1) project expenditure
- 2) product cost estimation
- 3) potential in revenue
- 4) ability to achieve the company's future goals
- 5) degree of risk of failing to meet objectives
- 6) level of technical complexity
- 7) circumstances with patents
- 8) meeting the criteria of the project
- 9) technology level of the product (state of the art)
- 10) availability of the technologies needed by the company
- 11) level of safety compliance
- 12) reliability of the product
- 13) level of accuracy
- 14) increases in efficiency

The first four evaluation items, together with the scoring and their explanations, are shown in Table 1.

The highest-ranked group of the three noted above depends on the state of the company. Regarding this (and the results of the above assessment), the operational side of an MRO (development of the operational methodology and planning) is ranked the highest. Hence, the present research continues to explore innovations that enhance the maintenance operational side of services utilizing digitalization, including the use of AI to determine the time and complexity needs of the work packages and scheduling optimization.

Table 1

Elements of the evaluation spectrum  
with description and explanation (created by author)

<b>Project Assessment and Prioritization</b>				
Specifications and Their Descriptions	Score and explanation of the assessment			
	0	1	2	3
<b>1. Project expenditure</b>				
- Required investment	- > 100 t€	- 50-100 t€	- 10-50 t€	- 1-10 t€
- Yearly project cost	- >40 t€	- 20-30 t€	- 10-20 t€	- <10 t€
- Needed FTEs (Full Time Equivalent)	- 3 or more man years are required	- 2 man years are required	- 1 man year is required	- less than 1 man year is required
<b>2. Product cost estimation</b>				
- Between minimum and maximum value based on products/similar solutions are available in the market.	- Highest product costs	- Medium-high product costs	- Medium-low product costs	- Lowest product costs
<b>3. Potential in revenue</b>				
- Based on the customer requirements, price/value ratio and market research (described in the Business Case).	- Lowest estimated product revenue	- Medium-low revenue	- Medium-high revenue	- Highest possible revenue
<b>4. Ability to achieve company's future goals</b>				
- Scale is defined according to the strategy and the relevances of the technical/operational roadmap items and based on MoSCoW method: M - Must have, S - Should have, C - Could have, W - Won't have.	- The outcomes won't have ability to achieve company's future goals.	- The outcomes could have ability to achieve company's future goals.	- The outcomes should have ability to achieve company's future goals.	- The outcomes must have ability to achieve company's future goals.

### 3. INTEGRATION OF AI AND DIGITALIZATION IN MAINTENANCE OPERATIONS

Aircraft maintenance services aim to provide high dependability, safety, security, and airworthiness standards. Maintenance actions are carried out in accordance with the client's tailored aircraft maintenance program (AMP) to achieve these goals. This program is based on the maintenance planning document (MPD). Additional tasks may be required by aircraft manufacturers or aviation authorities. The FAA [9] defines aircraft-specific needs as service bulletins (SBs), airworthiness directives (ADs), and customer-specific work. Manufacturers set a specific time for achieving each of these tasks and sub-tasks. However, when the MRO receives the sets of tasks—which is known as a work package—it is up to the company to reevaluate the time and set a new timing for accomplishment. Ultimately, the contract is signed with a pre-agreed-upon turn-around time (TAT) [10]. This period is essential for the upkeep process as airlines focus on ensuring their aircraft stay in service. Aircraft on the ground do not generate profit. Respecting the contract and the TAT agreement is one of the main milestones for operational excellence and market competitiveness.

Correctly predicting the time of the performance is the first step to achieving an optimized maintenance plan and schedule. Usually, MRO planners are responsible for predicting the manhours required for scheduled and unscheduled MRO activities. Unlike AI, humans mostly fail to notice complicated trends that result from a large amount of analytics and historical data. Precise forecasting can enhance the efficiency and income of MRO activities while decreasing TAT for aircraft operators.

Thus, forecasting methods and distribution models were employed to enhance job time estimation through data analytics [11, 12].

An artificial neural network (ANN) has been developed and tested in the present research using dummy data and, with emphasis on the multi-layer perceptron regressor, to improve the forecast accuracy for determining the time and complexity needed for work packages. The results are promising, as the ANN was able to forecast the actual manhours required for various task scenarios. The outputs of this module, presented in Fig. 2, highlight the possibilities for further enhancement with minor modifications.

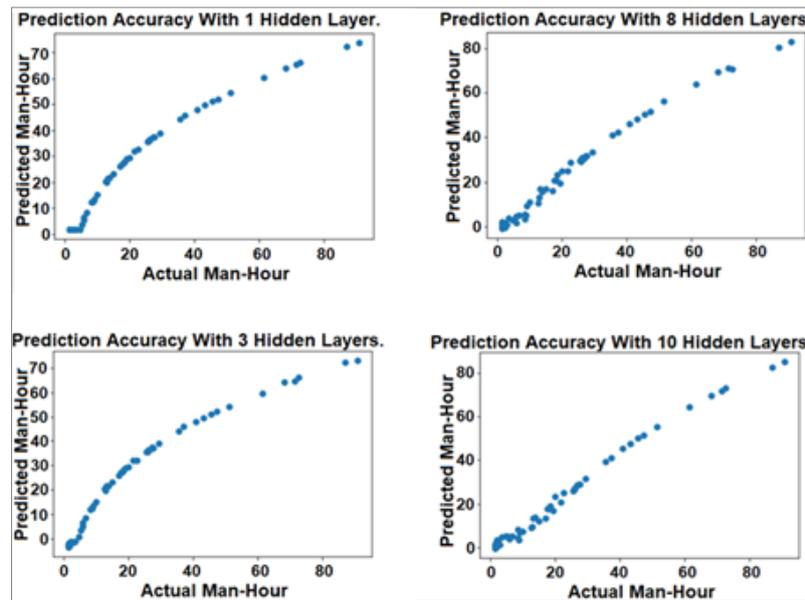


Fig. 2. ANN module output. (Created by the author)

This integration between AI and the daily workflow in MRO operational activities will improve the efficiency of planning processes, which will enable economic operators to make decisions aided by facts and data, thereby minimizing human-based errors. This, in turn, will save time and costs while strengthening airlines' relations with their customers.

#### 4. NEW MODEL FOR OPTIMIZING AIRCRAFT MAINTENANCE PLANNING AND SCHEDULING

Aircraft maintenance can be viewed as a complex process that requires meticulous planning, execution, and control. Project management principles are essential for optimizing maintenance activities [14]. Ultimately, adhering to the agreement and returning the aircraft punctually is a crucial aspect of market competitiveness. The timely delivery of an aircraft involves effectively managing all resources engaged to guarantee on-time performance and minimize operator wait times. However, outstanding maintenance tasks must be carried out simultaneously to guarantee that the aircraft remains dependable and fit for flying.

The MRO work setting is highly dynamic and depends significantly on various variables and factors. Therefore, it is complex and difficult to conduct proper and precise planning and scheduling for maintenance tasks and resource distributions (e.g., hangars, spaces, facilities, tools, consumable supplies, components, and capacities) with appropriate qualifications and authorizations. The range of aircraft types, the intricacy of maintenance tasks, constrained resources, and strict regulatory demands all play a role in creating a dynamic and complicated environment where effective planning and scheduling are essential for safe and economical operations. Considering these constraints, the research objective is to create and implement advanced optimization algorithms tailored for planning and

scheduling issues in aircraft MRO operations to aid decision-makers, planners, and upper management in enhancing their operations, making better decisions, and, in turn, increasing their orderings and profit.

Effective operational MRO processes should combine scope management, time management, and resource management [15-17]. A novel framework has been developed in the present research to comply with all three main points. This framework is called the Schedule Optimization Tool for Aircraft Maintenance (SOTAM), and it combines all required steps using an interactive interface with the ability to import files and archive solutions. This solution is explained in detail below.

After the process of importing the relevant files, a list of the aircraft is read to the program. The green ones (illustrated in Fig. 3) represent the already stationed aircraft, and the pink ones are the new incomers that the user wants to schedule. The figure also shows the stationary aircraft, the used slot, the TAT, the aircraft registration, and the type, among other data that the program has taken into consideration as important inputs to determine the possibility of placing the new incomers based on size in the first round and the theoretical insert possible slot.

SOTAM V2.08 - Slot Finder for a New Aircraft

Select Current A/C list C:\SOTAM\Example\01 - Current\_AC\_master\_Index.xlsx

Select New A/C list C:\SOTAM\Example\01.1 - New\_AC\_master\_Index.xlsx

Utilization

ID	MSN	Registration	Manufacture	Type	Customer	Starting Date	End Date	TAT	Slot
1	5413	WF-DFG	Airbus	A320	WZZ	01/04/2024 07:0...	05-06-2024 19:0...	65	5
2	745	VCD-CS	Airbus	A319	WZZ	05/04/2024 07:0...	22-04-2024 19:0...	17	3
3	9547	SC-CSVG	Boeing	B767-200	DLH	19/04/2024 07:0...	06-05-2024 19:0...	17	4
4	1241	DXV-VDX	Airbus	A380	DLH	07/05/2024 07:0...	24-05-2024 19:0...	17	2
5	5123	VDR-YH	Boeing	B737-400	BAL	01/04/2024 07:0...	31-05-2024 19:0...	60	1
6	1206	RG-G	Boeing	B767-300	BAL	15/04/2024 07:0...	30-05-2024 19:0...	45	6
7	875	HJ-LJ	Airbus	A321	RYN	25/04/2024 07:0...	04-06-2024 19:0...	40	8
8	1423	TRGHY-F	Airbus	A320	RYN	01/04/2024 07:0...	16-04-2024 19:0...	15	7
9	1501	HA-ABC	Airbus	A320	WZZ	10/04/2024 07:0...	05-05-2024 19:0...	25	Unknown
10	1502	HA-ABD	Airbus	A319	WZZ	05/04/2024 07:0...	05-05-2024 19:0...	30	Unknown
11	1503	HA-ABE	Airbus	A321	DLH	19/04/2024 07:0...	24-05-2024 19:0...	35	Unknown

Set the schedule date range:  
 From 01-Apr-24 To 05-Jun-24 View slot possibilities View slot possibilities for two A/C

Fig. 3. List of aircraft: stationary (green) and new incomers (pink). (Created by the author)

The next step is to determine all the possible theoretical solutions for insertion. Then, the user is given the option (see Fig. 4 for the HA-ABC registration number) to pick one solution to continue with the investigation of the tool and materials.

Concerning the next milestone, the user is requested to upload the aircraft work packages to run the optimizer and create a schedule for tasks with dispatched people, tools, and materials.

After uploading the work packages, the tasks are identified, the packages are broken down into smaller phases, and the priority of the performance follows the structure illustrated in Fig. 5. The aircraft identification is shown clearly, along with the total manhours of the package and the manhours required for every phase.

In the case of a tooling problem, the sub-step has been highlighted in yellow. Unavailable parts are indicated by pink. A shortage of tools and parts together has been defined as a blue sub-task. The user/planner has to decide whether to keep the aircraft in the same pre-picked slot or move it to a new slot. The next step of the scheduling optimization is the scheduling and distribution of people.

People scheduling and the final table of capacity distribution are determined to ensure the objective of the optimization process, which aims to enhance the efficiency of task planning and scheduling while considering time constraints. A worker's skill measurement factor or key performance indicator (KPI) was established for each individual on a scale from 0–9, reflecting their skills, experience, and record of executing a particular task [17]. The primary objective is to reduce downtime, thereby guaranteeing that the MRO company completes the inspection punctually by ensuring that all technicians are utilized effectively and efficiently. To meet both goals, the initiation and assessment of skill performance enables the module to assign tasks to the most skilled and experienced employees initially. Both objectives can

be met by focusing on maximizing the total value of all skills. Each technician has received a score ranging from 0–9 for each task based on previously archived maintenance data and management feedback. The results are shown as a calendar for people’s allocation in Fig. 6.

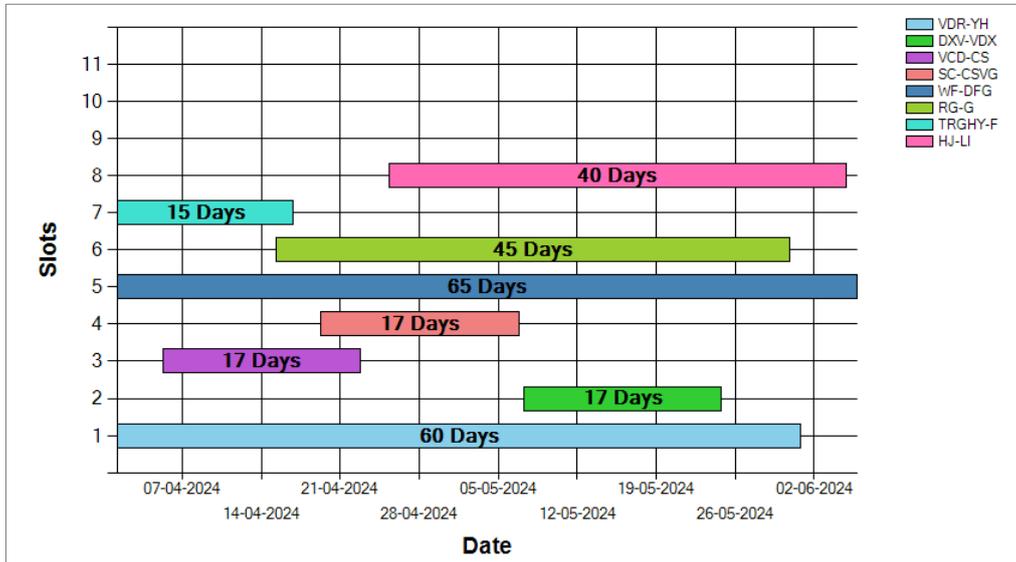


Fig. 4. Slot allocation and displacement of the aircraft. (Created by the author)

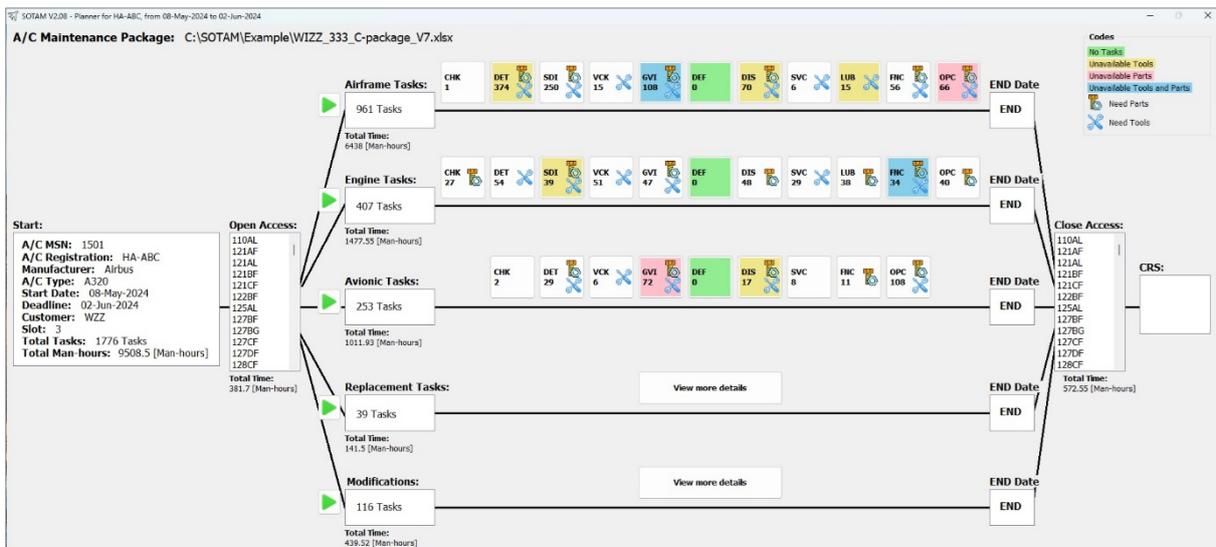


Fig. 5. The planner structure and interface. (Created by the author)

Naturally, employing a highly skilled and well-trained workforce is essential to maintaining the pace with similar developments in the field of MRO, as well as to achieve the futuristic visions that every MRO company is seeking and to stay relevant and capable of competing with other major competitors. Such high-value activities can be carried out by engineers with MSc or PhD degrees, who are currently scarce in the industry. A resolution can be achieved by creating an MRO MSc and PhD-level specialization programs aimed at enhancing the research and development process of the currently available methodologies and the operational workflow.

The educational structure of the new MRO specialization in MSc and PhD programs can be successful if university and company representatives take part in a steering committee, where the expectations, specifications, study plans, and requirements result from a mutual agreement.

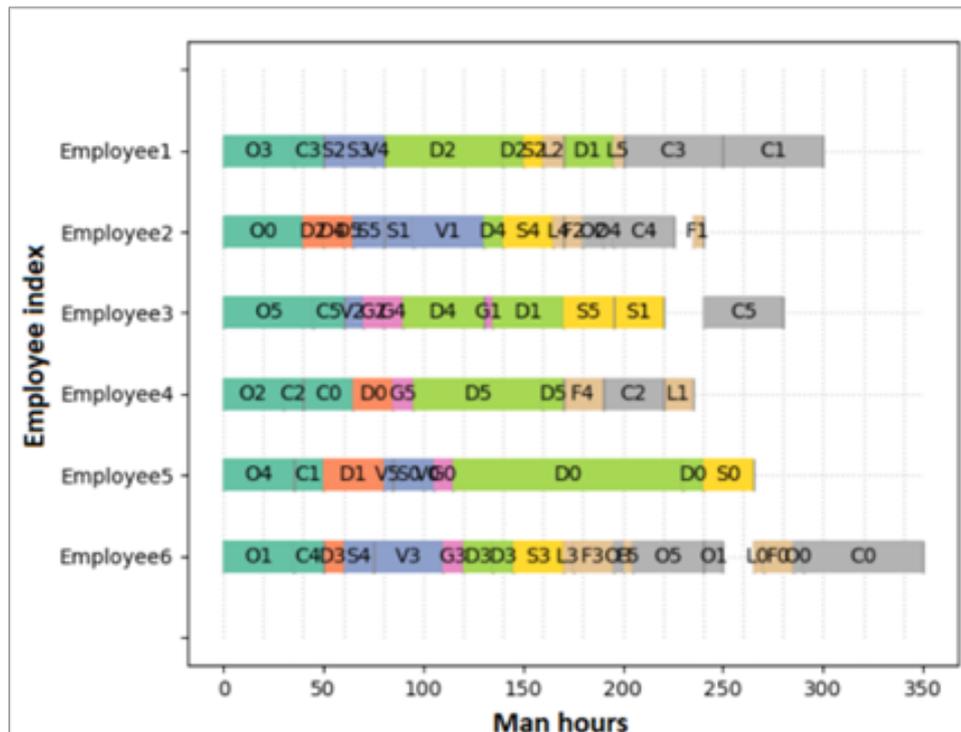


Fig. 6. Results of the workers' schedule. (Created by author)

## 5. CONCLUSIONS

Aircraft maintenance occupies a position of paramount importance within the intricate ecosystem of aviation operations. It serves as the bedrock upon which the safety, reliability, and economic viability of aviation are built. This paper explored the multifaceted nature of aircraft maintenance, moving beyond the traditional view of reactive repairs to encompass a proactive and strategic approach to asset management. It demonstrated that effective maintenance is not simply a cost center but rather a critical investment that yields substantial returns in terms of enhanced efficiency, improved operational efficiency, and minimized downtime. The integration of project management principles into maintenance operations has been highlighted as a key driver of success. By applying structured planning, resource optimization, and risk management techniques, MROs can streamline maintenance processes, control costs, and ensure that tasks are completed on time and to the highest standards.

A novel selection criterion was developed for prioritizing the future development areas of the roadmap. It considers regulatory requirements, company readiness, and future industry forecasts, and it provides a practical framework that the MRO enterprise can use to optimize its maintenance technology and allocate resources effectively. This roadmap, when combined with the implementation of robust and standardized procedures, will enable the MRO sector to achieve new levels of excellence in aircraft maintenance. Looking ahead, the pursuit of continuous improvement will be paramount.

By embracing data analytics, actively soliciting feedback from maintenance and administrative personnel, and remaining adaptable to evolving technologies and best practices, the aviation industry can ensure that aircraft maintenance remains at the forefront of safety and efficiency. Hence, AI was applied in the present work to determine the complexity and time needs of different work packages based on past data. Furthermore, using this information, a new method was developed for optimizing the planning and scheduling processes. The results were tested on a realistic mockup.

The human element remains crucial. A highly skilled and well-trained workforce is essential for translating technological advancements into tangible improvements in maintenance outcomes. Investing in training, fostering a culture of continuous learning, and facilitating cooperation between academic

and industrial entities are crucial for ensuring the quality and correct development of maintenance operations.

In an era of increasing complexity and ever-higher expectations, a commitment to continuous improvement in aircraft maintenance is not just a desirable goal but an absolute necessity for sustaining the long-term health and vitality of the aviation industry. Only through unwavering dedication to these principles can the continued safety and reliability of air travel be guaranteed for generations to come.

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