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# Technology Roadmap for Aircraft Maintenance, Repair and Overhaul

*Nowadays, the demand for aircraft Maintenance, Repair and Overhaul (MRO) is constantly growing. The market size of the European MRO segment is estimated to be USD 206.13 billion in 2022, growing at a Compound Annual Growth Rate (CAGR) of 2.8% between 2022 and 2030 [1]. This forecast is a good indication of the growth in the number of incoming assignments. As a result, airlines and aircraft operators will increasingly rely on companies with experience in the MRO field to perform maintenance and repair work. Furthermore, as many airlines now choose to outsource maintenance and repair, this will further increase the load on MRO companies. As the number of incoming jobs increases, the companies concerned are constantly looking for and implementing new and better methods and technologies, with another aim of gaining a larger market share. Moreover, as there is still scope for the development and introduction of new technologies and processes in this area, a significant number of research and development projects are underway or in the pipeline. Therefore, the main objective of this study is to use the available information to present a generalised technology roadmap for the companies involved in MRO activities and, on this basis, to collect, present and categorise the state-of-the-art developments in the MRO sector, highlighting what the future will hold for companies that incorporate these revolutionary innovations into their daily work processes.*

**Keywords:** *aircraft maintenance, repair and overhaul, strategy and roadmap, research and development activities, categorisation of MRO innovations*

## 1. Introduction

The act of maintenance is adopted in all industries to reduce the negative impact of failures and increase systems' availability at a minimum cost [2]. In any industrial facility, there are two main pillars: one is production (or operation) and the other is maintenance [3]. Maintenance is not equally relevant as a production process since maintenance is linked with costing money whereas production brings money to the businesses. But this is not accurate in the case of MRO providers because these companies offer their maintenance, repair, and overhaul services as their product, so to assure the flow of aircraft's operation, reliability and airworthiness, these services are needed by the airlines and they even rely on them.

Air transportation, in general, is defined to be continually growing in a competitive environment, despite the negative effect of Covid-19; the International Air Transportation

Association (IATA) forecasts that by the year 2023, the global passenger numbers are expected to exceed the pre-corona levels (105%) [4]. This expected growth in aviation traffic will increase the number of maintenance work packages and activities, so the MRO companies will have to handle more load since many airliners today choose to outsource their maintenance services. Outsourcing aims to reduce labour, training, tools and equipment costs [5]. Furthermore, establishing an MRO inside an airline demands a high capital of investment, which for some companies may not be available [6], and thus by outsourcing the maintenance services, the operators can focus their attention on operations within the scope of their core competencies while knowing that the best technologies and most efficient capabilities are utilised to maintain their fleet.

In addition to the added workload, there is still a high potential for technological development in the field of MRO and innovative processes, that can set an MRO company apart from others in the same region. The more advanced a company is the more it can handle the growing market and better compete with other major MRO facilities or even the manufacturers. By the end of the day, the goal is to ensure that an aircraft, engine, propeller, or any other component remains safe to fly or is used according to rules and regulations that are set by the Federal Aviation Administration (FAA) or the European Union Aviation Safety Agency (EASA).

By integrating these new systematic methodologies into daily workflow operation, the job can be done more effectively and accurately, while minimising the aircraft ground time and the unneeded costs and capacities. So, the focus of this paper will be on highlighting the new roadmap for the MRO companies' developments that are needed to remain in the competition. Additionally, the scientific categorising of these developments is going to take place also in the present work.

## 2. Developments of aircraft maintenance and repair in terms of aviation history

The aviation industry has come a long way since the Wright Brothers' first airplane invention back in 1903, in less than 120 years noticeable changes took place to further nourish this industry. Aluminium, fiberglass and composite materials [7] replaced wood and fabric, and thus the industry took a step further into establishing the "safety first" system that all people expect from it.

The materials of the airframe structures were not the only change, jet engines replaced propellers and so higher altitudes were reachable. Today research in different aeronautical science has taken place non-stop, many different areas and topics are still being conducted, which include, electrification [8], [9], hybrid aircraft operation [10], noise reduction [11], engine propulsion system [12], development of other engine's component [13] besides many others.

Like other aeronautical research topics, aircraft maintenance experienced similar developments, of course when the Wright brothers invented their first plane, there was no such thing as maintenance. But since then, the term became more and more familiar with time, and now the term relates to aircraft safety, airworthiness status and reliability. Tools and equipment were developed constantly. MRO companies raced to stay in the competition,

sought to obtain the latest technologies, trying to keep their customers satisfied by providing efficient, high-quality and low-cost services.

With every revolutionary innovation and technological achievement, the rates of accidents decreased, and the source cause of errors shifted from being mechanical-based to human-based [14], as indicated in Figure 1. So, gradually the machine became more reliable than humans.

Based on the above, nowadays humans are accountable for most hazards. In order to minimise the risk of human factors and to decrease the frequency of errors, the efforts are headed in the direction of raising safety and efficiency by adopting new methodologies, which can aid in the daily maintenance operation.
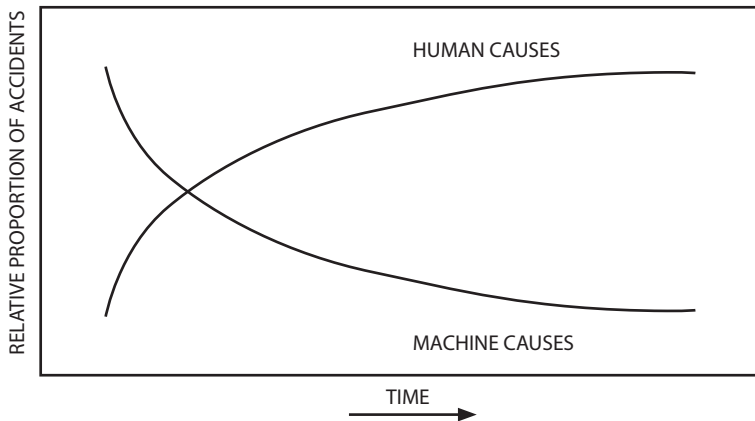


Figure 1.
*The cause of aviation accidents/incidents in a function of time* [14]

## 3. Workflow of the MRO service

Every MRO company's job scope is divided into two sections. The first is the technical one and the second is the operational one. Both sections are integrated, and they complete and support each other to a point that one cannot exist without the other.

The flow of work begins when an airline sends a work package to the MRO company to be carried out. Work packages are several maintenance tasks, each task is required to be performed within the pre-set interval or threshold of time by the authorities and manufacturers. These tasks get grouped together by the airline's engineering and planning technical team and then sent off to the selected MRO partner.

After receiving the package, the operational part begins, these tasks get studied thoroughly noting all the requirements needed to accomplish the job at hand, everything is mapped out: the skill required (mechanical, electrical, radio), aircraft zones, the tasks estimated man-hours, preparation time, materials, tools, facilities, qualifications, and when everything is ready and a plan is drawn, people get assigned to the aircraft and this is when the technical part starts while the operational one continues.

Technical means all the required work conducted to execute the tasks and dispatch the aircraft back to its operator. This includes all forms of inspections (structure and/or engines), lubrication of moving parts (with oil or grease), corrosion detection, calibration of equipment, repairing discrepancies (such as dents, scratches, corrosion), operational checks (for computers), functional checks (systems) and so many other jobs to ensure the safety and airworthiness of the aircraft.

Finally, when technical tasks are accomplished including revision, operation processes get involved again. Because every task performed needs to be signed, stamped and archived properly. After that, the completed package is sent off to the operators and the aircraft is certified to be released back into service.

## 4. Roadmap of MRO activities

As noted, the MRO workflow procedure includes a lot of human interventions on both operational and technical sides, and by looking into the scientific literature that is related to aircraft maintenance, it can be observed that in a similar way to other aviation research topics, the industry is trying to minimise the risk of errors and raise the safety bar even more.

Therefore, developments in both technical and operational sides of MRO are being presented with the integration of technological theories into them such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Deep Learning (DL) and many others. Of course, EASA has noticed this shift in interest towards more advancement and in order to govern this swift transition, they regulated it by publishing their first concept on the AI roadmap which is an initial vision of how the future is going to look like for air transport in the next decade [15]. This roadmap includes subjects such as AI trustworthiness, the effect of ML on the aviation industry, the estimated time frame for AI implementation and futuristic challenges.
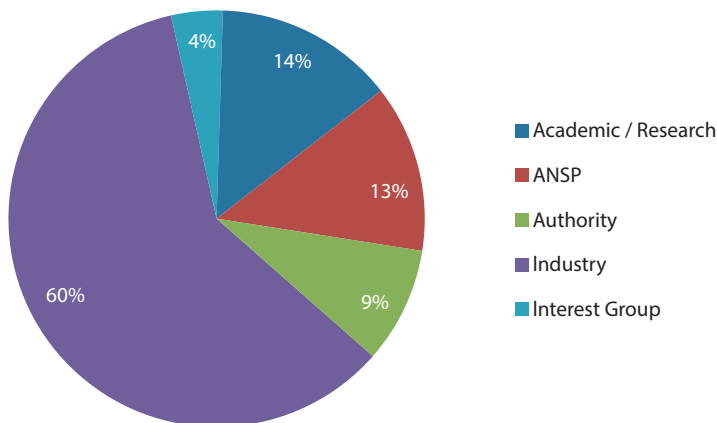


Figure 2.
*The result of the EASA consultation phase on the AI roadmap* [15]

This approach was offered to be discussed by stakeholders, academic researchers, Air Navigation Service Provider (ANSP) authorities and finally, the industry. The feedback was positive, the industry commented the most on this approach as illustrated in Figure 2, which means people in charge know the importance of these new methodologies [15].

It is known that maintenance goes hand in hand with aircraft technology, thus one cannot draw a good maintenance roadmap without taking into consideration aircraft manufacturing development and new configurations. So, maintenance evolves with aircraft technology.

With the start of aviation, the maintenance culture was very shallow, and some can even say that it was "non-existing", there were few sensors on the aircraft and so there was a low amount of data and information availability. Efforts were concentrated mostly on aircraft development and maintenance was neglected.

With time and digitalisation progress, more sensors were mounted to the aircraft structure and airframe leading to a higher amount of data that can be utilised to build Knowledge-Based Maintenance (KBM) [16]. Descriptive maintenance was first explored, it answers the question of "what happened?" by taking information from previous maintenance activities [16].

At present and with the increased amount of data available from history, diagnostic maintenance is being more used by analysing the data available and so answering the question of "why did something happen?". However, maintenance today is more costly than other services such as fuel for example plus human-based errors still may happen. Technological theories including robotics and the development of ML and AI algorithms are researched more often creating some scattered innovations, but these innovations are still not exactly common with MRO providers.

For the next decade, due to the required greener and more environmentally friendly load on the atmosphere, the developments are turning to low-emission and hybrid-powered aircraft. The maintenance cost will decrease at the integration of conventional and electric-based propulsion systems as the operational time over the certain duration will be less, and so the intervals between checks could be increased. The MRO-related culture is expected to get higher attention; it becomes even more demanding and uniform, meanwhile, the safety levels will be higher. The digitalisation of the processes and automation will spread more, which improves the working conditions (open office, home office), communication, transparency and sustainability as it results in less paper consumption. Furthermore, it reduces the errors by human factors further, workload for handling/transferring work packages, places for storage and can optimise the plan for budget, capacity, facility, inventory, tools and backlog with priority. The predictive maintenance – supported by digital twin applications – will replace previous diagnostic-based maintenance, and so the question "what will happen and when?" will be possible to answer by learning from the previous and predicted data. Furthermore, robots and drones, virtual and augmented maintenance, additive manufacturing, and new repairing technology development will be strongly presented under the supervision of humans, after being researched for so long, which will help also in minimising human-based errors.

As for the medium and long-term future, it is predicted that the industry will make a full transition to fully environmentally friendly and emission-free aircraft. This change is going to be challenging for MRO companies. For fully electric airplanes and with the use of batteries, condition monitoring, and further maintenance concepts are needed to prevent issues such as a thermal runaway. If the hydrogen driven aircraft are invented and spread, then this means

that maintenance activities will be as equally demanding as engines of today. Of course, new staff training and qualification requirements will be needed.

Finally, wider use of technological theories will be invested and more sophisticated algorithms will be available, perspective maintenance will take place allowing us to answer "how can we make something happen" or how to control the appearance of a certain event [16] and so almost eliminating human-based errors. The technical roadmap of MRO activities for the aeronautical sector is shown in Figure 3. Basically, this roadmap identifies the vision or statement in which several steps or milestones can be defined. There might be also various items within each step, then year by year and according to business value items get selected from this roadmap to be considered, and only when the Return of Invest (ROI) is reasonably high enough to be accepted then these items can be analysed and developed. This is shown by the various research conducted in this field. Every year companies and scientists update and take items from the roadmap to realise and develop them. The amount of work and research taking place in the maintenance sector proves that there is still a high potential for more process and technology development in this field.

## 5. Categorisation of MRO projects

By looking into the numerous research activity from the scientific world and in order to create some sort of guidelines for the countless articles and papers in this field, it was noticed that there were some similar traits between all of the published work in this area. Thus, a categorising of these topics was done, and it was concluded that only three main categories can integrate the majority of activities as follows.
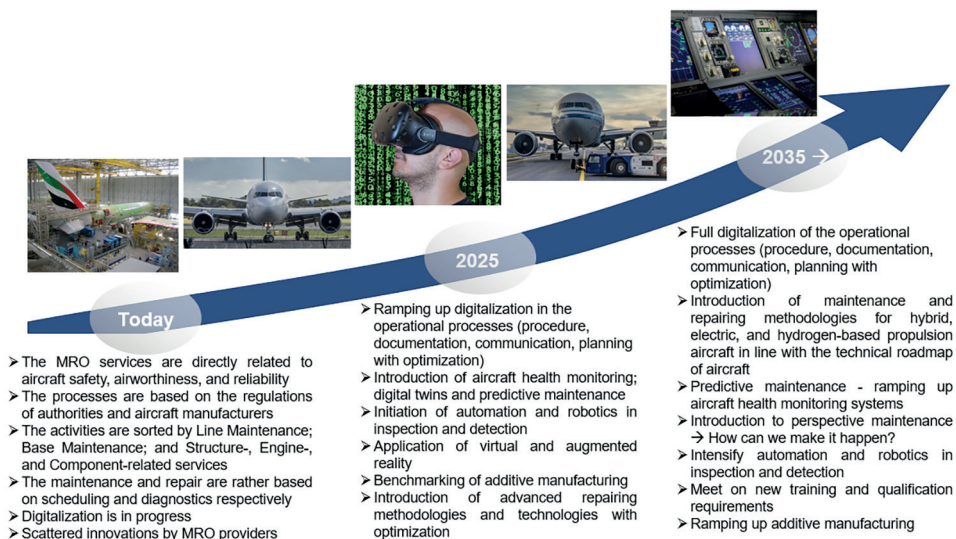


Figure 3.
*Technical roadmap of MRO activities in the aeronautical sector* (compiled by the authors)

## 5.1. Category 1: Development of the operational process

This category includes all the topics that relate to developing and optimising the daily operation workflow. For example, maintenance capacity planning and scheduling [17], [18], optimising MRO activities and sustainability through digitalisation [19], [20], innovation of education and aircraft maintenance training by using metaverses and Mixed Reality (MR) [21], [22], applying Lean principles and digital solutions for archiving the maintenance documents [23], and even the introduction of Augmented Reality (AR) technology in the development process of aircraft maintenance manuals [24].

From training to manuals and maintenance planning, these articles cover the submergence of technological theories into the operational side of the MRO processes. At the moment and since AI is still in its initial stages, it will only be used to aid and support companies in making better-calculated decisions under humans' supervision. However, when the AI algorithms reach a sophisticated level, no human interference will be necessary, so people can focus on more important tasks according to the EASA roadmap [15].

## 5.2. Category 2: Technology development for inspection and detection

Inspection is important for discrepancy detection. Aircraft are examined regularly during maintenance checks, either outside on an airport aircraft yard between flights, or in a hangar for longer-term inspections or heavy maintenance. Some inspections are part of the Maintenance Program Document (MPD) and are defined as routine or scheduled inspections. Others are non-routine inspections and occur after an unscheduled event like Foreign Object Damage (FOD) or corrosion detection.

Usually, the tools used to inspect either the airframe or engines are still highly dependent on humans. Mirrors and torch lights or even borescopes are famous for Visual Inspection (VI), and Detailed Inspection (DI), but the chance of a mistake while using these tools is quite high. Light reflection, eyesight issues, or even the mental state of the inspection mechanic play a great role in the accuracy of these checks. As a result, lots of research were conducted to develop the tools for inspection and detection with the help of technological theories listed above such as AI and ML, so the second category is dedicated to all the activity within the innovation of new inspection equipment.

For example, some researchers proposed utilising robots to aid in walk-around checks and pre-flight inspections [25] or performing airframe inspections as a collaboration between robots and mechanics [26]. Others introduced the Unmanned Aerial Vehicles (UAV) enhanced with image processing to monitor the airframe condition [27], or using AI to better detect fuselage corrosion [28], or even inventing a robot to do fuel tanks inspections [29].

## 5.3. Category 3: Process development in maintenance, repair and overhaul

The last category integrates the process of repair and maintenance. In this final branch, the researchers benefited from the big data to establish a firm base to transition from proactive to predictive maintenance, thus eliminating any unscheduled and sudden aircraft stops.

Models for predicting tires replacement were introduced by [30] and [31]. Structural health management was proposed by [32], defect prediction by means of digital twins was investigated by [33], troubleshooting was studied by [34], neural networks together with AI and ML were used by [35] and [36] to forecast lumpy demand.

In addition to predictive maintenance, this category also contains the new repairing methodologies and techniques, which include, besides many others integrating sensors in a repair patch to reduce crack growth but at the same time monitor the fatigue status [37].

## 6. Conclusion

Maintenance contributes significantly to aircraft operating expenses, flight delays and cancellations. Despite longer-lasting planes and more robust power plants, airlines now spend more money and time on maintenance than they do on fuel or staff. A big challenge is the ability to maintain fleets with high accuracy standards while decreasing MRO costs. Thus, there is a need for faster troubleshooting, automated aircraft inspection, improved planning and optimising processes. These needs are priorities for most aviation operators.

Since the aviation industry is a fast-growing business, the MRO providers have to adjust and comply with the requests of their customers to stay relevant and in the competition, this is why they responded by adopting new technologies, techniques and methodologies.

The academic world responded by drowning the market with all the developments needed to aid the MRO companies in handling the added load, and three categories were noticed that combine all the efforts conducted. These categories are shown in Figure 4.

These categories not only include all the scientific research but, in a way, they summarise all the aircraft maintenance work conducted inside this business environment.
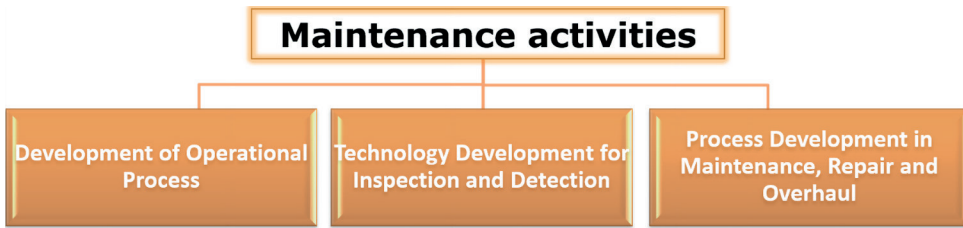


Figure 4.
*Aircraft maintenance work categories* (compiled by the authors)

Many advantages are expected from such innovations in both operational and technical such as the ability to map out short-term and long-term planning including manpower, facilities and tooling, plus the industry can raise the quality of the work conducted while decreasing the human-based errors.

If the research in the MRO field continued at the same pace as it is now moving, the future can be easily forecasted, we are heading towards more automation, more AI and more machines rather than human reliance in a way that fits with the EASA initial roadmap.

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## Technológiai ütemterv a légi járművek karbantartásával, javításával és nagyjavításával foglalkozó vállalatok részére

*Napjainkban a légi járművek karbantartása, javítása és nagyjavítása (Maintenance, Repair and Overhaul [MRO]) iránti kereslet folyamatosan növekszik. Az európai MRO-szegmens piaci méretét 2022-ben 206,13 milliárd USD-ra becsülték, ami 2022 és 2030 között várhatóan 2,8%-os összetett éves növekedési rátával (Compound Annual Growth Rate [CAGR]) fog növekedni [1]. Ez az előrejelzés az iparág fejlődése mellett a beérkező feladatok számának növekedését is jól mutatja. Ennek eredményeképpen a légitársaságok és a repülőgép-üzemeltetők egyre inkább az MRO-területen tapasztalattal rendelkező társaságokra támaszkodnak majd a karbantartási és javítási munkák elvégzésében. Továbbá, mivel ma már sok légitársaság a karbantartás és javítás kiszervezése mellett dönt, ez tovább növeli az MRO-vállalatok terheléseit. A beérkező feladatok számának növekedése miatt az érintett vállalatok folyamatosan keresik az újabb és jobb módszereket és technológiákat, illetve azok bevezetését, aminek másik célja a nagyobb piaci részesedés elérése. Továbbá, mivel ezen a területen még van lehetőség új technológiák és folyamatok kifejlesztésére és bevezetésére, jelentős számú kutatási és fejlesztési projekt van folyamatban, illetve körvonalazódik. Ezért e tanulmány fő célja, hogy a rendelkezésre álló információk felhasználásával*

*ismertesse az MRO-tevékenységben érintett vállalatok általánosított technológiai ütemtervét, valamint ebből kiindulva összegyűjtse, bemutassa és kategorizálja az MRO-ágazat legmodernebb fejlesztéseit rávilágítva arra, hogy milyen lesz a jövő azon vállalatok részére, amelyek ezeket a forradalmi újításokat a mindennapi munkafolyamataikba beépítik.*

**Kulcsszavak:** *repülőgép-karbantartás, -javítás és -felújítás, stratégia és ütemterv, kutatási és fejlesztési tevékenységek, Az MRO-innovációk kategorizálása*

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