Innovations in the Aviation MRO

Adaptive, digital, and sustainable tools for smarter engineering and maintenance

Stamoulis, Konstantinos

Amsterdam University of Applied Sciences

INAUGURAL LECTURE

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Konstantinos Stamoulis
Professor of Aviation Engineering

Creating Tomorrow

Innovations in the Aviation MRO

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Dr Konstantinos Stamoulis

Professor of Aviation Engineering

Amsterdam University of Applied Sciences

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1. Introduction

Aviation is recognised as one of the top advanced technology sectors that contributes to economic growth and societal development. Regardless of the current, unprecedent COVID-19 crisis, there are a number of challenges that the aviation industry is confronted with, not the least of which are related to a pressing demand for optimization in operations and a broader sustainability agenda. Within the context of aircraft design and development, composites and other advanced materials and manufacturing techniques are increasingly used and have contributed to significant weight reduction, which translates to reduced fuel consumption and emissions. More recently, new aircraft architectures and propulsion solutions are explored to select the best approaches and make further decisive steps for more efficient and cleaner aviation. In parallel, the corresponding manufacturing technologies and processes have been adapted, evolved, and automated. This enabled higher production rates for larger or complex structures with further reduction in weight, waste, cost and, ultimately, environmental impact. The adoption of these technologies and methodologies have transformed aircraft manufacturing and resulted in many breakthroughs.

At the same time, these transformations are creating new challenges, transitional processes, and a gap with reference to the corresponding maintenance, repair, and overhaul (MRO) practices, currently in use. MRO tasks vary from routine inspections to heavy overhauls, in which complicated tasks are typically characterized by unpredictable process times and material requirements. This is translated in large buffers in terms of labour and materials used and increased downtimes, leading to inefficient and expensive processes. Optimization of Aviation MRO operations has therefore been of high interest as it costs tens of billions of dollars annually. Moreover, as the complexity of the materials and structures increases, the maintenance complexity and unpredictability tend to also increase. For example, a characteristic concern is the long-term performance of the novel materials and composites structures, which are increasingly being introduced while at the same time, the MRO inspection and repair methodologies in use are insufficient to address the increasing demand, leading to time-consuming and labour-intensive processes. In general, MRO companies are currently striving to respond to pressing demand for decreased downtime, waste and costs without any compromise in quality and safety.

This book is both a short introduction to the recent developments, challenges and opportunities in Aviation Maintenance, Repair and Overhaul (MRO), and also a presentation and discussion of the research focal areas and the key waypoints towards smarter and more sustainable MRO. Innovation and integration have always been key aspects of Aviation. Currently, evolutions in aircraft design, materials and production techniques are ahead of the MRO practices in use. This gap is creating a demand for new knowledge to develop and operationalise adaptive, digital, and sustainable MRO tools, applicable or integrated in modern aircraft systems and components. Key enabling technologies including Data Science (e.g. Artificial Intelligence) and High-Tech Systems and Materials (e.g. Structural Health Monitoring and Additive Manufacturing) can enable the next step in maintenance processes and reshape MRO.

The Aviation Engineering Group seeks advanced technologies and methodologies to optimize MRO processes and reduce aircraft downtime through practice-oriented research. This research therefore actively contributes to helping aviation develop sustainable processes and is focused on two main topics: data analytics and prognostics to predict the maintenance needs and novel inspection and repair methodologies together with automated and sustainable tools to improve the maintenance implementation. In addition to applied research, the professorship is actively engaged in the educational process by incorporating research output into new knowledge and case studies for courses and modules of the Aviation degree programs, the CoPs of the Faculty of Technology, and various outputs of professional knowledge dissemination.

2. Background

2.1 Historical perspective of maintenance in Aviation

Any aircraft component or system is inevitably subject to failure mechanisms such as corrosion and fatigue, which gradually result in some deterioration of the original specification and operational performance and ultimately, in failure (Stamoulis, 2016). The goal of the Maintenance, Repair and Overhaul (MRO) processes is to cope with this deterioration or failure process and make the unserviceable component serviceable once again. In short, maintenance activities are carried out to keep an aircraft in its intended operational condition or to restore the airworthiness.

MRO is a traditional field, as old as aviation itself. In the earlier days of aviation, maintenance activities were mostly reactive or corrective, meaning that parts were only replaced or repaired after running into failure. Corrective maintenance proved to be unsuitable to safety-critical systems or in cases where the system failure causes huge costs. In the last half of the 20th century, MRO providers used corrective maintenance in a mix with preventive maintenance (PvM), a proactive strategy where systems and parts were maintained on fixed, predetermined intervals based on accumulated time and cycles, also known as scheduled maintenance. The main shortcoming of PvM is that the predetermined intervals are based on OEM design considerations, while actual conditions and usage may be quite different resulting in suboptimal utilization of material and labour.

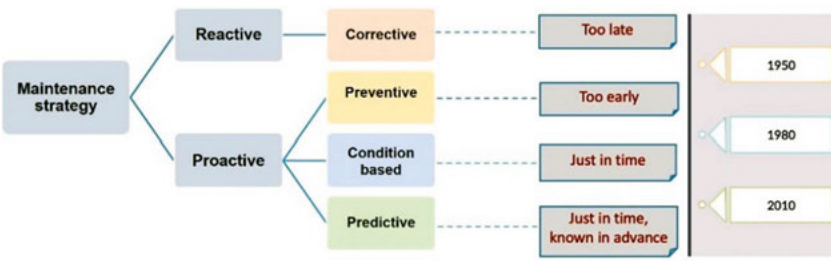

Figure 1: Classification and timeline of reactive and proactive maintenance strategies.

Another subtype of proactive maintenance strategy which was recently introduced is the condition-based maintenance (CBM), where recommended maintenance actions are based on information obtained through condition monitoring of the aircraft system or component. In literature, CBM and an even more proactive yet complex approach, the predictive maintenance (PdM), are applied interchangeably or linked implicitly. These approaches rely both on collected data and have a lot of commonalities, however they are focusing on different aspects: CBM in the actual condition while PdM is deploying prognostics (i.e., remaining useful life – RUL) to support the maintenance decision making (e.g., Tinga & Loendersloot, 2014 and Sprong, Jiang & Polinder, 2019). As the use of relevant data and reliable algorithms is essential to the operational deployment of CBM and PdM, there are numerous technical and operational challenges that need to be addressed to exploit their full potential (Stamoulis, 2021).

It is also important to note that the main difference between general plant maintenance and aviation maintenance is that MRO processes are mandated and monitored by regulatory authorities, such as the EASA and FAA, CAA and therefore the aircraft maintenance process is highly standardised, e.g., in MSG-3 (Maintenance Systems Group) and other directives. As a result of this highly regulated industry, there is a conservative approach by the different stakeholders in the operational deployment of novel methodologies and innovative technologies.

2.2 Status and challenges in Aviation MRO

Optimization of Aviation Maintenance, Repair and Overhaul (MRO) operations has been of high interest in recent years for both the knowledge institutions and the industry as a total of $69 billion has been spent on MRO activities in 2018 which represents around 10% of an airline's annual operational cost[1]. Moreover, the aircraft MRO tasks are often characterized by unpredictable process times and material requirements. Especially Small and Medium-sized Enterprises (SMEs) are typically challenged by unpredictable volumes, variability in tasks and uncertainty in workflow paths. In general, MRO companies constantly

1 For example, see IATA (2019), https://www.iata.org/contentassets/bf8ca67c8bcd4358b3d004b0d6d0916f/mctg-fy2018-report-public.pdf

strive to respond to the increasing demand for decreased downtime, waste, and costs without any compromise in quality and safety (Stamoulis, 2021).

Currently, most maintenance strategies employ preventive maintenance as an industrial standard, which is based on fixed and predetermined schedules. Preventive maintenance is a long-time preferred strategy, due to increased flight safety and relatively simple implementation (Phillips et al., 2010). However, its main drawback stems from the fact that the actual time of failure and the replacement interval of a component are hard to predict resulting in an inevitable suboptimal utilization of material and labour. This has two repercussions: First, the reduced availability of assets, the reduced capacity of maintenance facilities and the increased costs for both the MRO provider and the operator. Second, the increased waste from an environmental standpoint, as the suboptimal use of assets, is also associated with wasted remaining lifetime for aircraft parts which are replaced while this isn't yet necessary (e.g. Nguyen et al., 2019). The recently introduced CBM and PdM strategies aim to reduce maintenance costs and maximize availability by offering tailored programs that can potentially result in optimally planned, just-in-time maintenance meaning reduction in unneeded inspections and increase in availability. However, there remain several technical and operational challenges to be addressed to exploit their full potential. Moreover, another key issue is the criticality of the component under consideration which can determine the best compromise for the replacement interval and the optimum maintenance strategy to be followed.

At the same time, as the complexity of the materials and structures increases, the maintenance requirements and costs tend to also increase. A major concern is the relatively unknown long-term performance of the novel materials and lightweight composites structures which are increasingly being introduced. The state-of-the-art MRO inspection and repair methodologies are currently inefficient, leading to time-consuming and labour-intensive processes. Each non-destructive testing (NDT) technique has its own potential, however, it rarely achieves the capabilities for a full-scale diagnosis of possible defects and damage in a composite component (Borst, Stamoulis & Sprik, 2019). Current preferred NDT techniques such as Ultrasonic C-scan which require long inspection times and high level of human interaction, are additionally not efficient in testing complex composites geometries and cannot provide details on how damage or defects evolve and affect the service life of a component (Wang et al., 2020). Moreover, damages in composites structures currently lead either to extensive replacement or to time-consuming and labour-intensive repairs. There is still substantial work required to develop fast, reliable and efficient inspection and repair methodologies and realize their operational implementation in practical applications.

2.3 Digitalisation and Key Enabling Technologies (KETs)

Advancements in key technologies enable the adoption of novel approaches and methodologies and digital technologies to optimize aviation MRO by monitoring and predicting the aircraft status. Key Enabling Technologies (*KETs*[2]), such as Data Science, Artificial Intelligence (AI) and High-Tech Systems and Materials, e.g., Structural Health Monitoring (SHM) and Additive Manufacturing (AM) can enable the next step in maintenance transition from preventive to condition-based and predictive: aircraft can be kept in a safe and airworthy condition, and MRO processes are optimized by decreasing downtime and costs.

Some of the most promising examples include (Stamoulis & Apostolidis, 2022):

- Aircraft data of critical components with the use of sensors technology and effective data transfer and analytics can reveal the real-time physical status of the corresponding aircraft systems.
- MRO-specific, AI algorithms and simulation techniques enable faster diagnostics and prognostics, e.g., detection and assessment of hazards/defects/damages and Remaining Useful Life (RUL) estimation.
- Data-driven, scheduling tools can optimize fleet maintenance scheduling by determining maintenance tasks optimal slots and facilitating the decision-making.
- AI-based, automated inspection tools and additive-type, novel repair methodologies.

2.4 Societal and sustainability considerations

MRO organizations and systems are not limited in scheduling, inspection, and repair processes, but have many aspects that need to be considered such as human and societal challenges, not the least of which are related with human factors and sustainability.

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2 Kennis-en Innovatieagenda Sleuteltechnologieën, https://www.nwo.nl/sites/nwo/files/assets/20191015%20KIA-ST_1.pdf

A key issue towards the operational deployment of digitalisation and automation in MRO is the cultural and organisational transition since these innovations involve a complex interaction between humans and systems. Whether we are considering processes or tools, the interface between these digital systems and the human decision-makers or operators must be designed efficiently taking into account challenging human factors such as reluctance or reservations. To overcome these obstacles, a user-centric design has been proposed that organisational members are willing to trust and use (Ton et al., 2020).

Further, sustainable aviation is a strategic theme which involves all the stakeholders of the sector. The aviation industry works increasingly on a broad sustainability agenda[3], supported by demands from both the public and the government[4]. The technological solutions discussed in the previous paragraph are very promising, however, they cannot yet sufficiently respond to the operational challenges. There is an urgent need for practice-oriented research to develop methodologies and solutions in real-world problems.

The objective of the professorship is to contribute to the sustainable operational readiness across the industry, with the focus on improving the maintenance management and the technical operations.

First, the operational deployment of proactive-type strategies and efficient, digital maintenance tools can ensure (Stamoulis, 2021):

- Less unneeded maintenance and reduced waste of materials, which are currently replaced when this isn't yet necessary.
- Less deteriorated aircraft engines and systems that can operate at a higher efficiency, requiring less energy, which is translated to a better fuel consumption.
- Fewer operational disruptions, shorter lead times and overall decreased downtimes.

3 Air-France KLM Sustainability Commitments: https://www.airfranceklm.com/en/system/files/07_2019_-_sustainability_factsheet_afkl_en.pdf

4 Kabinet biedt financiële steun aan KLM als gevolg van de coronacrisis: https://www.rijksoverheid.nl/actueel/nieuws/2020/06/26/kabinet-biedt-financiele-steun-aan-klm-als-gevolg-van-de-coronacrisis

Further, the broad adoption of novel propulsion technologies will accelerate the transition to a cleaner aviation, including the use of sustainable aviation fuels and electric propulsion supported by the necessary infrastructure and design of maintenance.

3. Data, digitalisation and prognostics in MRO

3.1 The Predictive Maintenance building blocks

As the MRO providers try to address the complexity and uncertainty of the aircraft maintenance processes, the use of data-driven methods can provide meaningful information and insights into the way aircraft systems and components are operated and maintained. The rise of the so-called Industry 4.0 and the leverage of enabling technologies such as the Internet of Things (IoT) and the Artificial Intelligence have allowed the transition to a data-driven, predictive approach or a predictive maintenance strategy.

In the relevant literature, most authors and researchers agree on five required components to deploy a predictive maintenance approach (Stamoulis & Apostolidis, 2022), as illustrated in Figure 2:

1. Hardware: sensors installed and/or retrofitted in physical systems/parts.
2. Data acquisition: data transfer between the monitored asset and the data storage and data transformation so data can be stored in a useful form.
3. Data storage/management: platform on premises or in the cloud to ensure data storage, availability, and efficient transfer processes.
4. Data analytics: data pre-processing, so algorithms are fed with the right input and development of prognostic algorithms and models (e.g., Machine Learning and AI) to identify patterns or other useful information (RUL, degradation).
5. Decision support: tools used (e.g., Digital Twins) to determine actions based on the provided information.

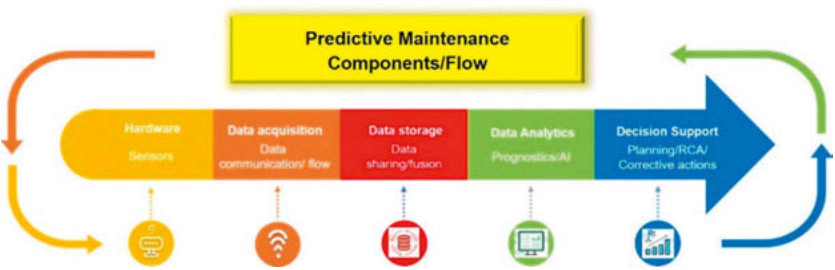

Figure 2: Components and flow chart of predictive maintenance.

Overall, added value is created by transforming the acquired data into predictions about the system condition and other relevant, meaningful information so that maintenance can be carried out when and where needed. However, currently in most cases, a few of the components or building blocks of the predictive maintenance process are in place so that developed solutions focus on these individual components and not in operationally deploy the full cycle. Several projects associated with this research direction are presented in section 5.2.

3.2 Data in aviation MRO

The introduction of data recording in aircraft was first envisioned as a measure to increase safety via the introduction of mandatory flight data recorders (FDRs) during the 1950s. The idea was that the technical details of an accident could lead to improved designs and prevent further accidents. Recorders' technology has improved significantly from analogue, capable of storing only four parameters, to digital on tape and then to solid state, able to record over 3000 parameters. Nevertheless, the scope of flight data recording remained relatively unchanged for decades.

In recent decades, as every new generation of civil aircraft creates more on-wing data and fleets gradually become more connected with the ground, a lot of barriers have been removed and an increased number of opportunities can be identified for more effective MRO operations. Today, data volumes are growing exponentially, e.g., an Airbus A350 generates and archives 50 times more data than an Airbus A320 i.e. from 12000 parameters and 8.3TB to over 670000 parameters and 450TB (Daily & Peterson, 2017). Therefore, data is increasingly becoming an asset for OEMs, aircraft operators and research organizations.

Some typical categories of data sources in Aviation MRO include:

1. Maintenance data
2. Flight recorder data
3. Sensors and Health Management systems data
4. External data
   - Weather data
   - Aircraft position data (such as ADS-B)
   - Benchmarking data gathered from similar systems or processes

3.3 Data management

The life-cycle maintenance planning of aircraft components is based on various techno-economic criteria, which make mostly use of heuristics, resulting in suboptimal solutions. At the same time, SME MRO providers underutilize their data, mainly due to data protection and focus on compliance. Other typical issues include the limited availability and low quality of historical data and the limited options in combining datasets from different operators of the same aircraft type. In addition, the availability of external data from airline operators, suppliers and manufacturers is hampered by confidentiality and ownership issues. Last, time-consuming data preparation work is often needed to make the data quality acceptable (Pelt et al., 2019).

MRO providers try to capitalize on this market, directly competing with the OEMs of airframes, engines, and systems. Three different categories can be identified:

1. Traditional MRO providers can be more independent in their services, eventually selecting the tools and methods they use from multiple providers however they have limited accessibility to big data.
2. MRO providers who are at the same time aircraft operators are a separate category. The competitive advantage of those organizations is that as MRO providers are benefited from the large operational data pools of their airline businesses, which can be used for training their analytics models. Nevertheless, in this case, data accessibility and ownership are complex issues.
3. The third category is OEMs which usually have a better understanding of the technical aspects of their own products, however, they do not operate aircraft commercially. As a result, they rely on their customers to access operational data, a process that faces reluctance from the airlines since they see the danger that their data will also benefit competition indirectly. As a result, complex legal agreements are usually needed, making data accessibility challenging.

Several new data capturing, manipulation and sharing technologies are currently being developed, with the potential to change the landscape in data management. For example, data can now be organized effectively with the use of modern Big Data technologies. However, the availability, sharing and combination of data is still an issue that has technical and legal challenges. A promising solution is Federated Analytics (FA) technology which can be developed and act to combine and analyze datasets and algorithms located in different geographical locations, without compromising confidentiality or ownership (Nilsson et al., 2018 and Li et al., 2020). The FA can provide a promising approach to MRO end users without risking unauthorized exposure of their data. The same applies to operators with legal, labor-related or geographical limitations in sharing their data. However, such concepts have only been tested in lab conditions. Before operational deployment a validation of the expected benefits is required by running experiments of real-life operational data for different components and by measuring the benefits in accuracy.

3.4 Data analytics and algorithmic methods

The key to unleash data potential and deliver meaningful insights lies in analytics. Before starting the analysis and dive into specific methods and techniques, it is important to define the goal and the precise research question(s). For example, is the objective to detect abnormal behavior of an aircraft system or to predict the remainining useful life of a component? The goal to determine the KPIs and the variables, i.e., the input and target variables (Pelt et al., 2019).

There are numerous schemes in the literature (e.g., Han et al., 2012) that can be used to classify the data analytics & algorithmic methods. In terms of technical complexity, a method can be one or any combination of the following (Apostolidis, Pelt & Stamoulis, 2020):

1. Fairly simple, making use of visualization techniques can be used for descriptive, exploration, monitoring and communication purposes.
2. Simple to moderate, consisting of a wide range of statistical data mining techniques such as correlation to identify patterns and meaningful information from large pools of data
3. Complex, using sophisticated, high-fidelity machine learning and AI algorithms for prognostics and recommendations for decision-support systems.

Overall, added value is created by transforming the acquired data into knowledge, reasoning, predictions, and ultimately, decisions and actions. Nevertheless, each problem must be approached with the appropriate, feasible and relevant method. Then, it can be determined if the benefits outweigh the investment taking also under consideration that the increased complexity is not necessarily an advantage. For example, complex and not transparent AI methods can create reduced confidence and certification issues while simpler methods, more relevant with the standard practices and engineering logic might be more attractive in certain cases.

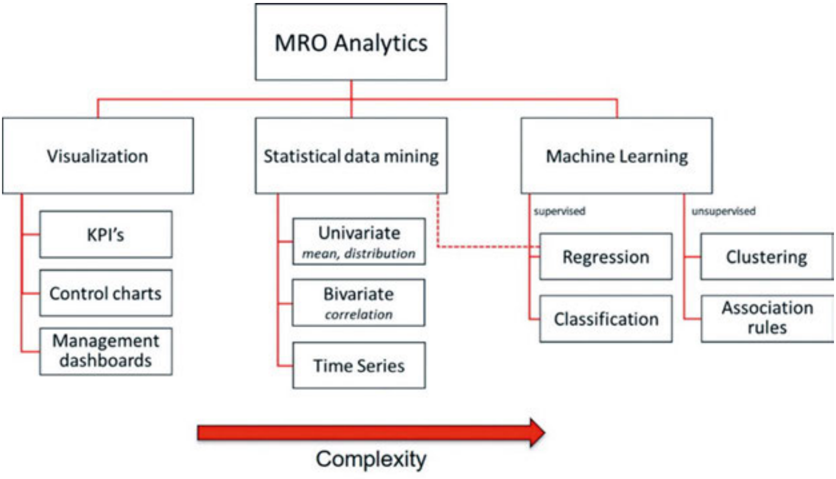

Figure 3: Classification of Data analytics in MRO.

3.5 Digital twins

Digital Twins (DT) are currently considered as a promising approach to address the problem of unpredictability in MRO operations. A DT is the combination of multiple state-of-the-art technologies embedded in three distinctive components, which are the physical entities in the physical world, the virtual models in the virtual world, and the connected data that tie the two worlds together (Grieves, 2014). However, it is not a fundamentally new concept, as it is rooted in a wide range of conventional system simulation and control methods (Glaessgen & Stargel, 2012).

There is no unique definition of a DT in literature. Nevertheless, it is generally agreed that a DT can be considered as a detailed digital representation of the physical components of an aircraft system with the use of relevant data from various sources, such as real-time sensor data and historical maintenance data, a combination that can describe, optimize and predict the performance behaviour and the Remaining Useful Life (URL) of an aircraft system or an MRO process with the use of simulation, prognostics, diagnostics, and analytics (Liu et al., 2018). This digital representation provides information about the current operational status of an aircraft component, with the benefit of exploring and investigating different operational and maintenance scenarios before their execution (Li, C., et al., 2017).

Simulation models can employ data-driven, physics-based or hybrid methods to replicate the physical status of a device (Tidriri et al., 2016). Artificial Intelligence and other data analytics methods can also be used to match the device's behavior and project it to future operating conditions (West & Blackburn M, 2017).

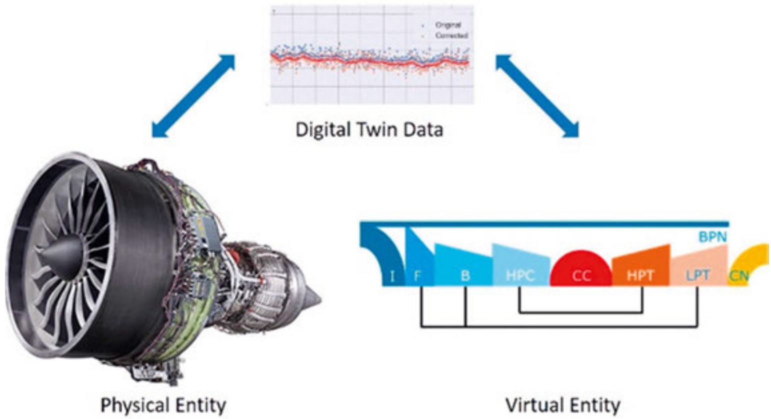

Figure 4: Digital Twin (Apostolidis & Stamoulis, 2021)

A Digital Twin enables operators to understand, predict, and optimize the performance of their physical assets or analyze the behavior of a device after a failure or a technical issue (Apostolidis & Stamoulis, 2021). In addition, simulation models can play a crucial role in designing new maintenance practices for systems and assets. This practice can be assessed in the virtual environment and deployed in the physical one (Qi & Tao, 2018). This way, an MRO provider can run experiments that will lead to an optimal operation of their assets. Nevertheless, various technical limitations complicated the development of effective Digital Twins, as it required technical maturity from a group of necessary enablers, such as the data-related and the Internet of Things (IoT) infrastructure for effective communication between the physical and the virtual device (Wright & Davidson, 2020).

3.6 Decision support tools and human factors

The ultimate building block of a predictive maintenance flow is the application of the data analysis output into recommendations for decision making and actions to improve the MRO efficiency. Predictive analytics can significantly reduce downtime, waste and costs through labour, inventory and material management and processes optimization without any compromise in quality and safety.

Individual case studies conducted with the use of a wide range of data and analytics proved to be successful in delivering better information and prognostics including (Pelt, Stamoulis & Apostolidis, 2019):

1. Accurate monitoring of performance degradation.
2. Faster troubleshooting and root cause identification.
3. Prediction of remaining useful life of components.

Nevertheless, a major challenge to be addressed is the cultural and organisational transition towards the operational deployment of data-driven, decision support systems and tools. The human factors related to this transition include reluctance and reservations by human decision-makers in use of automatically calculated information and recommendations. To overcome these obstacles, a user-centric design has been proposed that organisational members are willing to trust and use (Ton et al., 2020).

4. MRO challenges and innovation opportunities for aircraft novel materials, structures and propulsion technologies

4.1 Composite materials in aviation

Since the 1960s, the aerospace industry has increasingly been incorporating composite materials due to their superior mechanical properties (e.g., specific stiffness and strength) and their competitive, through-life environmental behaviour such as fatigue and corrosion resistance. These characteristics make them preferred materials for lightweight and more efficient structures, which is translated into reduced fuel consumption and emissions. Nevertheless, it was not until 2005 when composites became the principal construction material in civil and military aircraft[5], with primary, wing and fuselage structural components applications as illustrated in Figure 5.

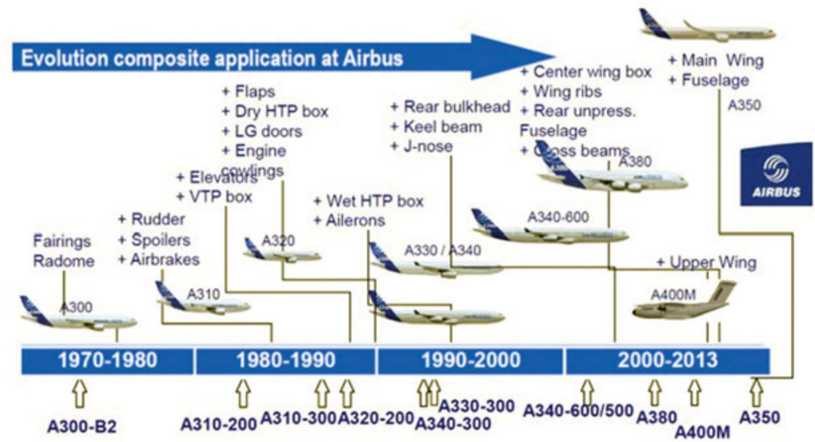

Figure 5: Evolution in composites aircraft applications (Airbus, 2013)

5 Composites are used for up to 50% per weight, in modern civil (e.g. Boeing 787, Airbus A350) and military aircrafts (e.g. NH90, F-35)

The increasing use of composites in place of traditional metallic alloys creates new challenges in inspection and damage assessment, as composites are non-homogeneous and anisotropic[6] materials. Moreover, it is well established that aircraft composite structures are particularly susceptible to impact damage where induced damage can occur within numerous locations at various levels of scale, making it difficult to efficiently detect and assess (Schijve, 2009). Damage accumulation within a composite is closely related to the actual strength and lifetime prediction of the component. Especially, the occurrence of barely visible impact damages (BVID) in composite components is a serious problem, which threatens the structural safety of an aircraft, and should be timely detected (Stamoulis et al., 2020).

4.2 Mature and emerging inspection methodologies

Currently, inspection techniques that are certified and used in aviation MRO are largely labour-intensive and slow processes that are carried out by human operators. These techniques are based on a wide spectrum of methodologies but are typically time-consuming and highly dependent on the operator. MRO technicians are trained and certified in various non-destructive techniques and required to periodically repeat this process to be able to perform inspections.

Non-Destructive Testing (NDT) state-of-the-art

Several NDT techniques built upon different methods (Figure 6) are used for inspections during the lifecycle of an aircraft part. These NDT techniques include the most established and widespread wave-based methods of ultrasonic testing (UT) and acoustic emission, and other, emerging methods such as optical-based laser shearography and terahertz testing or computed tomography. Nevertheless, the certified state-of-the-art NDT tools and methodologies are currently inefficient, requiring in most cases, access to the local aircraft area of interest and/or disassembly tasks with a consequent increased aircraft downtime.

Further, each NDT technique has its own potential but rarely achieves the capabilities for a full-scale diagnosis of possible defects and damage evolution in a

6 Composites exhibit anisotropic mechanical properties (e.g. strength) due to orientation of the reinforcement material; That is, their properties vary depending upon which geometric axis they are measured along, as opposed to metallic materials

composite component (Borst, Stamoulis & Sprik, 2019). For example, current preferred NDT techniques such as Ultrasonic C-scan which require long inspection times and high level of human interaction, are additionally not efficient in testing complex composites geometries and cannot provide details on how damage or defects evolve and affect the service life of a component (Wang et al., 2020).

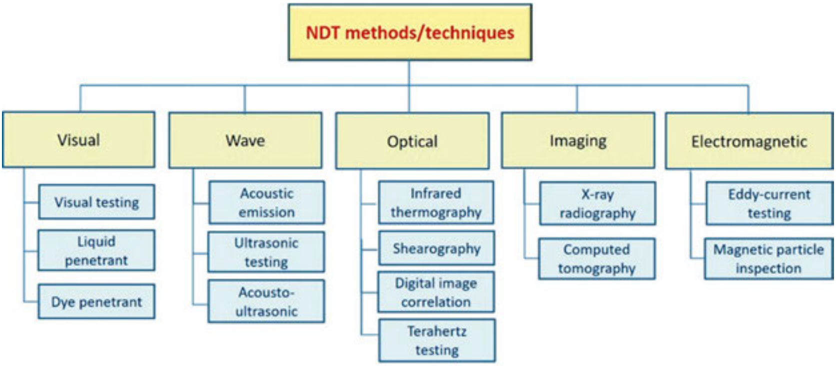

Figure 6: Classification of NDT techniques in groups associated to used methods.

Overall, as the volume and structural complexity of composite parts continue to grow, the cases of multi-NDT techniques are becoming increasingly important in maintaining structural integrity. Ongoing research in this approach is also growing with the use of fusion techniques to combine results from different NDT methods (e.g. Xiao et al., 2019). An example of a multi-domain tool, i.e., 3D structural light scanning/lock-in thermography/laser shearography, capable of providing the complete technical status of the composite component in one inspection step has been recently proposed by NLR[7].

Despite recent promising theoretical research results and proof of concepts with the use of AI-based, automated systems (e.g., Mahmod et al., 2019) in improved NDT techniques, there is still substantial work required to develop fast and affordable systems for both equipment and data processing methods to promote their practical implementation in industry.

7 http://www.composite-maintenance.com/dcmc-innovation-tracks/nondestructive-research-in-service/

Structural Health Monitoring (SHM) and CBM implementation

To address the NDT limitations and drawbacks, the concept of Structural Health Monitoring (SHM) has been recently explored. SHM is defined as "the process of acquiring and analysing data from on-board sensors to evaluate the health of a structure"[8]. The data obtained from an SHM system can be used for the implementation of a condition-based maintenance (CBM) approach which was introduced in section 2.1. By means of a continuous monitoring and an early fault detection, severe damage can be avoided, allowing efficient timing of maintenance tasks, and avoiding unnecessary inspections at the same time.

The main SHM techniques include vibration, strain-based fibre optics and guided waves methods (Aliabadi and Khodaei, 2018). SHM has been implemented for rotating machinery, with significant costs reduction and safety increase in maintenance tasks. Nevertheless, the equivalent laboratory SHM concept for fixed structures has not yet scaled-up to real aircraft structures application. The main reasons for the slow adoption by industry are the necessity of extensive validation and the requirement that methods have to be proven to be robust and demonstrated on different structures and realistic servicing conditions (Cawley, 2018). Further, there is a need for improved, reliable raw data collection by SHM sensors and robust SHM algorithms (Güemes et al., 2020).

4.3 Automated and innovative repair methodologies

Currently, MRO repairs in aviation typically include manual and slow processes that are highly dependent on the operator skills. In addition, the damage assessment process is characterized by the limitations, that are elaborated in section 4.2, and also dependent on manual, time-consuming and inaccurate inspection techniques. These conditions are often translated in inefficient or expensive repairs leading to increased downtime and additional costs.

Robotics for automation

As a logical consequence of the advancements in automation of aircraft manufacturing and in particular the automation of composite structures production, more attention is recently paid to the automation of MRO. Automation of composite repairs offers the possibility of faster and more reliable repair processes by increasing accuracy and consistency, especially in the case of complex

8 According to SAE Standard ARP6461

geometries. The entire process from a damaged to serviceable component can be divided into six phases (Figure 7) as observed in practice and supported by literature[9].

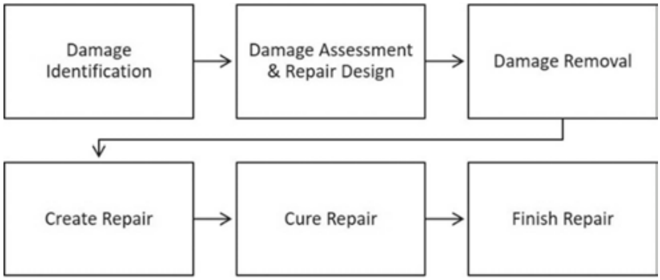

Figure 7: Typical MRO composite repair process (Borst et al., 2020)

Several parties are working on solutions for automation of composite repair operations including 3D scanning and measurement of the damaged area as well as material removal and repair execution by a robot or a cobot. Examples are found at Lufthansa's CAIRE, a mobile device for removing material layers, while hanging onto the structure using suction cups[10] and the Reply5 machine by BAYAB using water jet abrasion for removing layers of fibres[11].

Advanced welding and additive manufacturing-type repairs

In addition to the automation of conventional, mechanical machining processes for repair, recent research focuses on the application of advanced welding processes and additive manufacturing (AM)-type techniques. Especially, aircraft engine components are exposed to extreme operational conditions to increase the overall aircraft performance, therefore there is an increasing need for efficient repair strategies to increase the lifetime of such high-value components. Novel welding processes such as the Cold Metal Transfer (CMT) are promising techniques that offer significant benefits including reduced distortion by minimizing heat input and a faster, cost-efficient, and easily automated process

9 EASA, "AMC25.1309(b)(5)," EASA.
10 Lufthansa Technik, "Upside down: robot for inspection and repairs," 21 May 2020. [Online]. Available: https://www.lufthansa-technik.com/caire-repair-robot.
11 F. Cenac, "Automated abrasion – La revolution for composite material repair," 12 March 2020. [Online]. Available: https://www.bayab.fr/en/composite-material-maintenance-2-2/.

as compared to conventional welding techniques, e.g., dabber Tungsten Inert Gas (TIG) welding.

Then, the AM techniques have already proved their potential in manufacturing lighter and more efficient aircraft structures from fewer parts. For example, GE Aviation very recently completed the prototype testing of a new turboshaft engine with extensive use of AM. This prototype serves as the technology pipeline to meet next generation, engine requirements and expected to meet a series of aggressive performance goals including a 35% reduction of fuel consumption and a 45% reduction of production and maintenance expenses, as compared to current engines[12]. Regarding the MRO sector challenges, AM-type, deposition techniques such as the High-Pressure Cold Spray (HPCS) and the Laser Direct (Energy) Deposition (LDD/LDED) provide promising fast, quality and cost-effective means for repairing or remanufacturing damaged aircraft engine parts and systems to further extend their service life. For example, an HPCS repair process has been developed[13] for the repair of corroded and worn helicopter gearbox components (Kay & Karthikeyan, 2016). Moreover, experimental studies succeeded in repairing damaged turbine blades based on a new semi-automated algorithm using an LDD technique (Wilson, 2014).

4.4 Novel propulsion technologies

More recently, new aircraft architectures and propulsion solutions are explored to select the best approaches and make further decisive steps for a more efficient and cleaner aviation. [14] These solutions include four different propulsion technologies (Stamoulis & Apostolidis, 2022):

1. Full-electric aircraft aiming predominantly in the regional, commuter segment due to the battery energy density limitation.
2. Hybrid electric aircraft which offer possibilities for various operational combinations and degrees of hybridization and are aiming at short- to medium-range applications.

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12 https://www.ge.com/additive/additive-manufacturing/industries/aviation-aerospace
13 MIL-STD-3012, "Cold Spray Manufacturing Process Standard.
14 NLR-CR-2020-510, "Destination 2050: A Route To Net Zero European Aviation" Feb 2021. [Online]. Available: https://reports.nlr.nl/bitstream/handle/10921/1555/NLR-CR-2020-510-public.pdf?sequence=4&isAllowed=y

3. Hydrogen aircrafts that still face several volume and storage related challenges and will expected to provide solutions in the medium and long-range segments.
4. Sustainable alternative fuels that are the only foreseeable solution to address the long-haul flights.

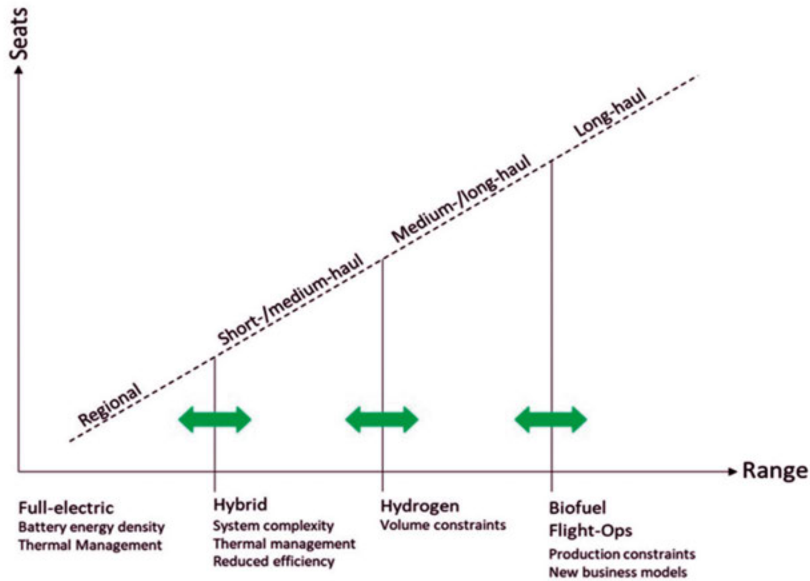

Figure 8: Novel propulsion technologies and their expected operational deployment[15]

For the successful transition to cleaner low-emissions aviation, several challenges associated with the respective technologies must be addressed (Figure 8) while there is still a gap in the analysis and design of the necessary maintenance strategies and infrastructures.

15 Graph by A. Apostolidis, Aviation Engineering Research Group (2020).

5. Applied research in Aviation MRO engineering

5.1 Research focus

The Aviation Engineering professorship seeks advanced technologies and methodologies to optimize MRO processes and reduce aircraft downtime through practice-oriented research. This research therefore actively contributes to helping aviation develop sustainable processes and is focused on two main topics: data analytics and prognostics to predict the maintenance needs and novel inspection and repair methodologies together with automated and sustainable tools to improve the maintenance implementation.

The professorship will pursue the following research directions with direct applications to the MRO domain:

- Data analytics and prognostics for transition to condition-based and predictive maintenance.
- Non-destructive testing, structural health monitoring, and damage assessment innovations with focus on composite structures and engines parts.
- Novel repair methodologies including automation of repair processes (e.g., robotics, additive manufacturing).
- Design of maintenance for sustainable propulsion solutions (e.g., maintenance of electric aircraft and sustainable aviation fuels).
- Human factors and safety systems.

These research directions fit well with the High-Tech Systems and Materials (HTSM) top sector[16] and especially with the challenges, priorities and research topics of the roadmaps Aeronautics[17] and Smart Industry[18].

16 The HTSM roadmaps are bottom-up initiatives from science and industry within the Top Sector. In their subdomain, they include applications and technologies, priorities and implementation, and partners and process, see: https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/Documenten/KIAs/HTSM%20Knowledge%20and%20Innovation%20Agenda%202018-2021.pdf

17 HTSM Top Sector, Roadmap Aeronautics 2020 – 2025, 31 August 2020. [Online]. Available: https://www.nlr.nl/wp-content/uploads/2021/05/HTSM-Roadmap-Aeronautics-2020-2025-Final-2020-08-31.pdf

18 Smart Industry roadmap, Research agenda for HTSM, ICT and the route for NWA, 28 August 2020. [Online].Available: https://www.nlr.nl/wp-content/uploads/2021/05/Roadmap-Smart-Industry-2020.pdf

5.2 Data analytics & prognostics for MRO

Data analytics and prognostics can significantly reduce downtime, waste and costs through labour, inventory, and material processes optimization in MRO without any compromise in quality and safety as described in Chapters 2 and 3. The Aviation Engineering professorship has previously completed a RAAK MKB applied research project on data mining in MRO and recently initiated new research on predictive maintenance and MRO decision-support systems in collaboration with TU Delft and KLM. These studies are offering new insights in efficient maintenance strategies and optimization tools. Further, a new research project proposal on AI-based, cross-industry MRO optimization solutions to reduce energy, material and labour waste is in application status (Horizon Europe Framework Program).

Data mining in MRO (RAAK MKB, completed)
The Aviation Engineering research group in cooperation with the aviation industry has conducted an applied research project (2016-19) to explore MRO optimization with the use of data mining methods. More than 25 cases have been studied at eight different MRO enterprises. The CRISP-DM methodology is applied to have a structural guideline throughout the project. Individual case studies conducted with statistical and machine learning methods were successful at prediciting, among others, the duration of planned maintenance tasks as well as the optimal maintenance intervals, the probability of the occurrence of findings during maintenance tasks. The research resulted in new insights in maintenance methods, decreased MRO lead times and significant cost savings.

Predictive maintenance (R&D Mobility Fund, approved)
This study includes the development of AI-based predictive maintenance (PdM) models in collaboration with TU Delft and KLM Engineering & Maintenance. The models are developed and validated by using historical data from non-safety critical, aircraft cooling system. Further, a federated analytics architecture has been employed to address the data scarcity and data sharing challenges. Therefore, datasets are combined from multiple operators, located in different geographical locations to create value for all parties without compromising confidentiality or ownership. Finally, the contribution of the PdM models to decision support systems is investigated by exploring which corrective actions are best suited to different outputs of the models.

MRO decision-support systems (R&D Mobility Fund, approved)
This study is related with the outputs of the Predictive Maintenance study of the same project in collaboration with TU Delft and KLM. The project objectives include the development of decision support tools at three different levels, as follows:

- An MRO simulator for maintenance concepts evaluation at a strategic level, on aspects such as fleet availability, reliability, and costs.
- A scheduling optimization tool for fast and efficient planning at a tactical level.
- Decision-support tools for human resources planning at an operational level to increase efficiency and minimize potential disruptions.

5.3 Innovations in inspection and repair tools

Advanced materials such as composites have become the principal construction materials of modern aircraft structures despite their shorter track record and their relatively unknown long-term performance. At the same time, the MRO inspection and repair methodologies in use are inefficient to address the increasing demand and complexity, leading to time-consuming and labour-intensive processes as described in Chapter 4. This gap is creating a demand for new knowledge to develop and operationalise adaptive, digital, and sustainable MRO tools, applicable in modern aircraft systems and components. The Aviation Engineering professorship is currently participating in a RAAK MKB project on the automation of composite repairs and will participate in a four-year project on Smart MRO together with a Dutch consortium that includes KLM, JetSupport, NLR, TNO and TU Delft.

FIXAR – Automation of composite repairs (RAAK MKB, ongoing project)
This applied research project is co-funded by SIA-RAAK, and involves three Universities of Applied Sciences (AUAS, Inholland, Saxion) and a consortium of Dutch SMEs. The objective is to support Small and Medium Enterprises (SMEs) by implementing knowledge and new technologies which in the case of FIXAR focus on the automation of repair procedures. The explored automated repair processes include 3D scanning and measurement of the damaged composite area as well as damaged material removal carried out by a robot or a cobot. The research program is ongoing and will have a project delivery deadline in March 2022.

Smart MRO – Innovations in inspections and repairs of aircraft composites and engines parts (R&D Mobility Fund, approved)
This four-year project aims to develop innovative and efficient inspection and repair methodologies that are applicable in modern aircraft systems and components such as composite structures and engine parts. AUAS is collaborating with a Dutch consortium that includes KLM, JetSupport, NLR, TNO and TU Delft. Main research activities include the development of innovative, non-contact NDT techniques for composite components and engine parts, automated 3D measurement system and image processing methods for complex geometries as well as the application of advanced additive manufacturing-type techniques in MRO. Overall, the objectives are the increased automation and integration of MRO processes and the reduced waste by minimizing the unnecessarily rejected, high-value aircraft parts.

5.4 Human factors and safety systems

The Aviation Engineering professorship has been active in addressing Human Factors & Safety (HFS) problems for both large organisations and SMEs. The professorship performs applied research related to real-life cases and problems, having as a goal to improve and innovate professional practice to support an information-driven aviation environment and the effective deployment of advanced decision-making systems. Earlier contract research projects on MRO safety yielded preliminary results following the study of a large MRO, located in Asia. These projects followed the bottom-up principles of Safety Differently (SD), and utilising tools such as Work-As-Done (WaD), Work-As-Imagined approach (WaI), and micro-experiments to close the identified safety gaps. In addition, a RAAK PRO research project has been conducted on developing metrics for Safety Management Systems (SMS) in Aviation which resulted in the development of two tools for organisation's SMS and safety culture. Further, a future research project in preparation is also described next to this end.

Measuring safety in aviation (RAAK PRO, completed)
The Aviation Engineering professorship has conducted a four-year (2015-2019) RAAK PRO funded applied research project on developing metrics for SMS and Safety Culture. The identified problem was lack of sufficient data to monitor safety performance, and lack of objective criteria to that end. The aim of this project was thus to help aviation organizations verify the safety performance of their organizations. The project developed two tools, namely AVAC SMS and

AVAC SPC: the former tool measures three areas within an organization's SMS and the latter measures three areas in the organization's safety culture pre-requisites to foster a positive safety culture.

Safety systems in MRO (RAAK PRO, in preparation)
Following the conceptualisation of alternative safety metrics (RAAK PRO, 2015-2019) based on the effectiveness of risk controls, the scarcity of resources and system complexity, further research needs are identified to determine whether these provide viable solutions in MRO organisations, and to address the research gap in MRO safety systems. The latter problem was also scoped via research on maintenance incident data that show the problematic reporting elements and a compliance culture approach, hindering data and, as a result, safety systems decision making in MROs. Organisations following a compliance approach commonly aim to gather as much data as possible, overlooking data quality. In addition, challenges in SMEs remain and are linked to variability (of operations, data, etc.) and lack of predictability. Hence, the objective of this proposal is to address risks in continuing airworthiness and maintenance and to support the MRO's complex transition to a predictive strategy via proactiveness and predictive quality performance data.

5.5 Sustainable propulsion solutions

Small aircraft are expected to fly fully electrically by 2030 and then from 2050, it is expected that regional aircraft will also use new propulsion configurations, such as hybrid electric: partly on kerosene, partly electric as also described in Section 4.4. Further innovation such as hydrogen aircrafts and flying-V architecture are also currently explored. The Aviation Engineering professorship contributes to targeted sustainability research initiatives, such as the Dutch Electric Aviation Centre (DEAC), a national research centre set up to promote electric flight and Sustainable Aviation Fuel pilot projects in collaboration with KLM.

Maintenance of electric aircraft (Dutch Electric Aviation Centre, approved).
The Aviation Engineering professorship contributes to the Dutch Electric Aviation Centre (DEAC) which promotes electric flight. The initiative is a collaboration between Delft University of Technology, Deltion College, and the AUAS. For the successful transition to cleaner, low-emissions aviation, several challenges associated with the respective technologies must be addressed while there is still a gap in the analysis and design of the necessary maintenance strategies and

infrastructures. As a part of our work at DEAC, the research group is collaborating with TU Twente in mapping the needs of maintenance of electrical aircraft.

Sustainable Aviation Fuels (Bright Sky consortium, MRO working group)
This study is conducted under the Bright Sky consortium, in collaboration with KLM Engineering & Maintenance. In general terms, MRO providers aim to move towards SAF-compatible operations, to accommodate this kind of demand and at the same time reduce their environmental footprint. Specifically, these pilot projects aim to investigate three aspects of SAF engine MRO. First, to understand the impact of SAF in engine performance during testing, so the results are compatible with the current, standard processes. Second, to investigate the effects of SAF in engine parts and secondary systems, such as the fuel pumps, oiling systems, seals etc. This will reveal the maintenance particularities of SAF fuel blends. Last, as engine testing with the use of SAF will become a standard practice in the future, the details of such an endeavour need to be determined mostly the aspects related to fuel supply, storage and operational procedures.

6. Impact on higher education and knowledge dissemination

In addition to applied research, the Aviation Engineering professorship is actively engaged in the educational process by incorporating research output into new knowledge and case studies for courses and modules of the Aviation programs, CoPs of the Faculty of Technology, and professional masterclasses. Further, the objective of the research group is to upscale collaborations and contributions in higher degrees (Masters, PDEs and PhDs).

6.1 Impact on Aviation Bachelor Program

The two Aviation professorships – Aviation Engineering (AE) and Aviation Management (AM) – currently focus on four of the Aviation program's themes: Maintenance, Repair and Overhaul, New Repair Methodologies and Safety and Human Factors (AE) and Airport and Space Capacity (AM), as shown in Figure 9.

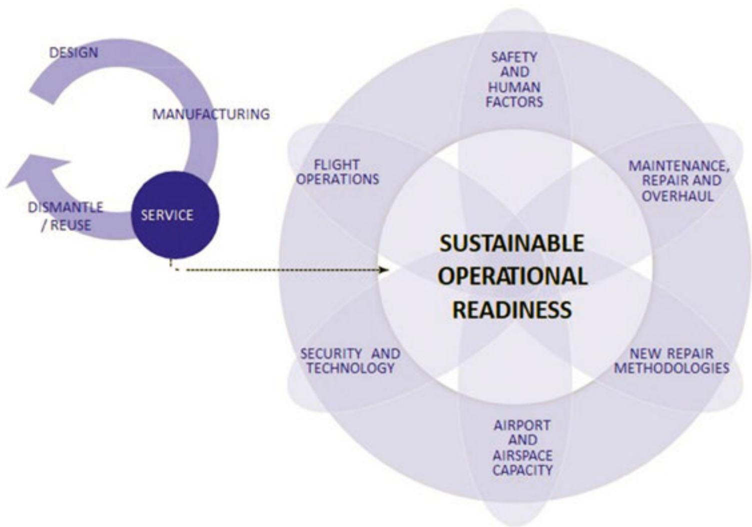

Figure 9: Aviation program's themes for education and research

Aviation Engineering track

The Aviation Engineering professorship is associated with several learning lines including Aircraft Systems, Structures and Materials, Maintenance and Life-Cycle Management and Regulations, Security and Safety, and various courses including Airframe Mechanics, Gas Turbine Performance, Aviation Maintenance Management, and the MRO Repair and Modification Design specialization track. A crucial objective here is to continuously bridge the gap between applied research and education by translating and incorporating research outcomes into new knowledge and professional projects and products for the educational modules.

In addition, the professorship actively contributes to the curriculum committee of the Bachelor Program as well as to the recently started curriculum redesign process. The aim is to revise the body of knowledge and skills (BOKS) and develop a flexible, effective but also coherent curriculum that will motivate the students and help them to further develop their professional and personal talents. As presented in the earlier chapters, the Aviation MRO industry encompasses a variety of complex and multidisciplinary assignments (see also mind map in Figure 10). Having only profound knowledge in a unique field is no longer sufficient. Therefore, next to a sound technical knowledge, the modern engineer must also exhibit basic knowledge of adjacent domains (e.g. logistics, data analysis) or general disciplines (e.g. business, safety, sustainability) to become more of a so-called T-shaped professional.

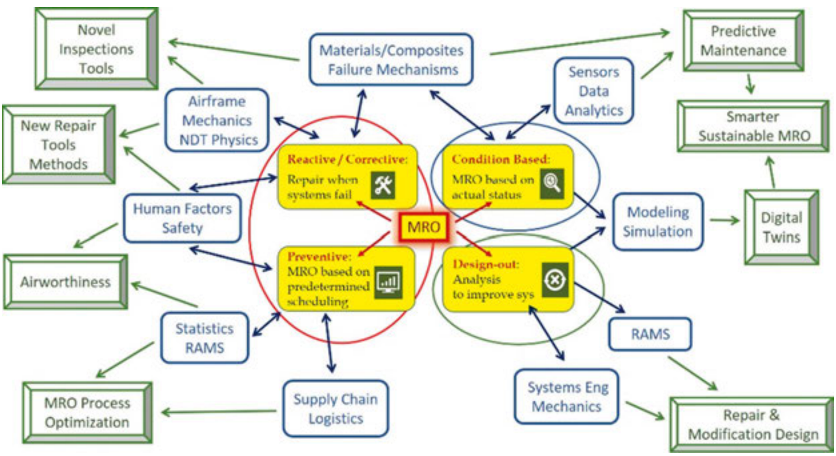

Figure 10: Multidisciplinary nature of Aviation MRO domain

That being the case, the redesigned curriculum follows a more integrated approach of engineering and operations themes in years one and two. This approach ensures a broad basis in terms of knowledge and competencies and supports an overarching, combined theme of “Sustainable Operational Readiness”, i.e., the optimum and sustainable deployment of aircraft and the supporting infrastructure, systems, and procedures. In addition, the goal of the project group is the integration of education and research from the very first introductory modules to the final graduation thesis project.

Aviation Honours Engineering Program
The Aviation Honours Engineering program offers students a well-rounded education in research, innovation, and technology. This program is based on interactive lectures and workshops from lecturers, researchers and professionals that support students to create innovative solutions for Aviation’s engineering real-world problems. The knowledge level in the Honours program is higher than the regular specialization tracks of the Bachelor program while additional research skills are developed and practised during the program. Honours projects’ themes are aligned with ongoing research themes of the Aviation Engineering research group.

Higher degrees programs
The Aviation program is currently collaborating with Embry-Riddle Aeronautical University in the part-time Master of Aviation Maintenance (MAM) degree program for professionals. The objective of the MAM program is to provide knowledge and develop skills and abilities necessary for students to become effective supervisors, leaders, and managers in the aviation maintenance industry. The program is also suitable for professionals who have experience in supervisory and managerial roles and are committed to a lifelong learning for continuing professional development.

The objective of the professorship is to upscale collaborations and contributions in higher degrees (Masters, PDEs and PhDs).

6.2 Impact on Faculty of Technology (FT) profile themes and CoPs

In line with the recently established “Education and Research Vision of the Faculty of Technology (FT)” in 2021, an ongoing faculty-wide redesign of courses is focusing on Communities of Practice (CoPs) and connecting students, lecturers, researchers, and the professional field, with a focus on technical and innovative solutions for practical issues. In addition, the new vision offers room for more personal learning paths and flexibility. To generate even more focus, mass and impact in education and research, the FT focuses on recognizable profile themes, relevant to society and the professional field within the Amsterdam Metropolitan Area (MRA). These profile themes provide a framework for relevant and quality education and research and are elaborated in sub-themes in CoPs (year 3 and 4 bachelor's degree programs).

The Aviation Engineering research group is associated with several CoPs under development including "Zero emission transport and infrastructure" (Connectivity & Mobility), "Clean mobility" (Energy transition), "Predictive maintenance", "Design, materials & manufacturing futures", "Intelligent systems" (Smart industry) and "Human technology interaction", "Forensic decision making" (Technology for life). We also contribute to the development of the new Faculty studios, such as the new Maintenance and Data Studios, which offer great potential for collaboration and synergy within and outside the Faculty of Technology.

Predictive Maintenance CoP
In this cross-sectoral CoP, we are focusing on the operational deployment of predictive maintenance (PdM) approaches. The employment of a predictive maintenance methodology creates added value by transforming the acquired data into predictions about the condition of a system/asset and other relevant, meaningful info (e.g., RUL) so that maintenance can be carried out when and where needed. The related PdM methodologies are elaborated in Chapter 3 while the research topics are presented in Section 5.2.

6.3 Knowledge dissemination and professional masterclasses

The Aviation Engineering research group contributes to knowledge dissemination by various outputs in the form of technical reports, panel discussions, conference presentations and peer-reviewed publications. Moreover, a two-day international conference entitled "Aircraft Technology, MRO and Operations" was organized in 2019 and offered a forum where multidisciplinary knowledge was shared and discussed with participants from both academia and industry. A new edition of this international conference is organized for 2023.

Further, knowledge developed by research outcomes is disseminated towards the professional international working field by means of masterclasses, i.e., short, workshop-type, professional courses. Currently, an increased number of these professional masterclasses are being developed with the objective to be integrated into one coherent portfolio centered around "Sustainable Operational Readiness". An example of the new masterclasses directly related to the ongoing research of the professorship is the masterclass "Applications of AI in Aviation MRO".

Applications of AI in Aviation MRO

This masterclass aims at provide a clear understanding of the potential of data-driven methods in Aviation MRO. The maintenance of aircraft is a very complex and expensive activity, which is currently characterized by numerous deficiencies. Participants are provided with a thorough overview of the technical areas that can be improved with the employment of AI-based methods. As aircraft operators aim to understand the behaviour of their assets over a long period of time, the use of data-driven methods can provide additional insights into the way these assets are operated, maintained and replaced. Artificial Intelligence has the potential to identify patterns in technical data produced by the aircraft systems and reveal valuable information about the physical status of these systems. Different use cases are presented and discussed, revealing a way towards efficient and sustainable maintenance operations.

Acknowledgements

This book reflects insights and ideas gained over approximately 30 years in various appointments within the aviation sector, spanning from engineering and maintenance management to teaching and research.

I thank the board of AUAS and especially Geleyn Meijer, and André Henken, Dean ad interim and Esther Ras, current Dean of the Faculty of Technology, for providing me with the opportunities that come with my appointment as Professor of Aviation Engineering.

I also thank my colleagues Geert Boosten, Sannie Bombeeck, Monique Heiligers and Janette Bezemer, as well my former colleague Robert Jan De Boer for their continuous support and collaboration from the first day I joined AUAS.

Furthermore, I thank my colleagues at the Aviation program and especially the Aviation Engineering researchers Asteris Apostolidis, Maria Papanikou and Maaik Borst who have already made many contributions to the research output, feedback on the educational curriculum, and impact on the professional practice and society. Our research group is currently developing close relationships with other programs and labs within the Faculty of Technology. I highly appreciate the collaboration with our colleagues, and I am looking forward to upscale these synergies within the Communities of Practice and Labs within AUAS.

Finally, I would like to thank my family and certainly my wife Maria for her endless support.

References

Aliabadi and Khodaei, "Structural Health Monitoring (SHM) for Advanced Composite Structures", Comput. Exp. Methods Struct., 2018.

Apostolidis, A., Pelt, M., Stamoulis, K.P., "Aviation Data Analytics in MRO Operations: Prospects and Pitfalls", Proceedings of IEEE RAMS 2020, Palm Springs, CA, USA, 2020.

Apostolidis, A., Stamoulis, K.P., "An AI-based Digital Twin Case Study in the MRO Sector" Transportation Research Procedia 56, 55–62, 2021.

Baptista, M., Sankararaman, S., de Medeiros, I.P., Nascimento, C., Jr., Prendinger, H., Henriques, E.M.P., "Forecasting fault events for predictive maintenance using data-driven techniques and ARMA modeling" Computers and Industrial Engineering, 115, pp. 41-53., 2018.

Borst, M. S., Stamoulis, K., Sprik, R., "Evaluation of NDT Techniques for CFRP Characterization and Damage Assessment", Society for the Advancement of Material and Process Engineering (SAMPE) Europe Proceedings, ISBN: 978-90-829101-1-7, Nantes, France, 2019.

Borst, M. S., Stamoulis, K., Wijnhoud, S., Lugtenburg, P., "Automation of composite repairs: a preliminary study", Society for the Advancement of Material and Process Engineering (SAMPE) Proceedings, Amsterdam, Netherlands, 2020.

Cawley, P. "Structural health monitoring: Closing the gap between research and industrial deployment", Structural Health Monitoring, 17(5), 2018.

Daily, J., Peterson, J., "Predictive Maintenance: How Big Data analysis can improve maintenance" In: Richter, K., Walther, J. (eds) *Supply Chain Integration Challenges in Commercial Aerospace*. Springer, 2017.

Deng, Q., Santos, B.F., Curran, R., "A practical dynamic programming-based methodology for aircraft maintenance check scheduling optimization", European Journal of Operational Research, 281(2), 2020.

Glaessgen E. and Stargel D., "The Digital Twin Paradigm for Future NASA and US Air Force Vehicles" 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, AIAA Paper 2012-1818, 2012.

Grieves, M., *Digital twin: Manufacturing excellence through virtual factory replication.* White paper, Florida Institute of Technology, 2014.

Güemes, A., Fernandez-Lopez, A., Pozo, A.R., Sierra-Pérez, J., "Structural Health Monitoring for Advanced Composite Structures: A Review". Journal of Composites Science, 4(1), 2020.

Han, J., Kamber, M., & Pei, J., *Data mining: Concepts and techniques*. 3rd ed. San Francisco, CA: Morgan Kaufmann Publishers, 2012.

Kay, C.M., & Karthikeyan, J., *High Pressure Cold Spray: Principles and Applications,* ASM International, 2016.

Li, C., Mahadevan, S., Ling, Y., Wang, L., Choze, S., "A dynamic Bayesian network approach for digital twin", Proceedings of the 19th AIAA Non-Deterministic Approaches Conference, Grapevine, TX, USA, 2017.

Li, T., Sahu, A.K., Talwalkar, A., Smith, V., "Federated Learning: Challenges, Methods, and Future Directions," IEEE Signal Processing Magazine, 37(3), pp. 50-60, 2020.

Liu, Z., Meyendorf, N., Mrad, N., "The role of data fusion in predictive maintenance using digital twin", AIP Conference Proceedings, 1949, art. no. 020023, 2018.

Mahmod, M.F., Bakar, E.A., Ramzi, R., Harimon, M.A., Abdul Latif, N., Mustapa, M.S., Ismail. A.E., "Artificial neural network application for damages classification in fibreglass pre-impregnated laminated composites (FGLC) from ultrasonic signal". In: Proceedings of the 10th International conference on Robotics, Vision, Signal Processing and Power Applications, Singapore: Springer, 2019.

Nguyen, D.V., Kefalas, M., Limmer, S., Apostolidis, A., Yang, K., Olhofer, M., Bäck, T., "A review: Research and Application of Prognostics and Health Management in Automotive and Aerospace Industries", International Journal of Prognostics and Health Management, 10(2), 2019.

Nilsson, A., Smith, S., Ulm, G., Gustavsson, E., Jirstrand, M., "A Performance Evaluation of Federated Learning Algorithms" Proceedings of the 2nd Workshop on Distributed Infrastructures for Deep Learning, 2018.

Pelt, M., Apostolidis, A., de Boer, R.J., Borst, M., Broodbakker, J., Patron, R.F., Helwani, L., Jansen, R., Stamoulis, K.P., "Data Mining in MRO", Faculty of Technology, Amsterdam University of Applied Sciences, 2019.

Pelt, M., de Boer, R.J., Schoemaker, C., Sprik, R., "Ultrasonic Verification of Composite Structures", EWSHM – 7th European Workshop on Structural Health Monitoring, Nantes, France, 2014.

Pelt, M., Stamoulis, K., Apostolidis, A., "Data analytics case studies in the maintenance, repair and overhaul (MRO) industry", MATEC Web of Conferences, 304 04005, 2019.

Phillips, P., Diston, D., Starr, A., Payne, J., Pandya, S., "A review on the optimisation of aircraft maintenance with application to landing gears" In: Kiritsis, D., Emmanouilidis, C., Koronios, A., Mathew, J. (eds) *Engineering Asset Lifecycle Management*. Springer, London, 2010.

Qi, Q., Tao, F., "Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison," IEEE Access, 6, pp.3585-3593, 2018.

Schijve, *Fatigue of Structures and Materials*, Springer, Netherlands, 2009.

Sprong, J. P., Jiang, X., Polinder, H., "A Deployment of Prognostics to Optimize Aircraft Maintenance – A Literature Review", Annual Conference of the PHM Society, 11(1), 2019.

Stamoulis, K. P., Panagiotopoulos, D.I., Pantazopoulos, G.A., Papaefthymiou S., “Failure analysis of an aluminium extrusion aircraft wing component”, International Journal of Structural Integrity, Vol. 7, p. 748-761, 2016.

Stamoulis, K. P., Georgantzinos, S.K., Giannopoulos, G.I., “Damage characteristics in laminated composite structures subjected to low-velocity impact”, International Journal of Structural Integrity, 11(5), 2020.

Stamoulis, K.P., “Advanced data analytics and digital technologies for smart and sustainable maintenance”, ISATECH 2021 – International Symposium on Aircraft Technology, MRO & Operations, Budapest, Hungary, 2021.

Stamoulis, K. P., Apostolidis, A., *Diagnostics, Prognostics & Advanced Maintenance Technologies for Aviation MRO,* Springer, 2022, in preparation.

Tidriri, K., Chatti, N., Verron, S., Tiplica, T., “Bridging data-driven and model-based approaches for process fault diagnosis and health monitoring: A review of researches and future challenges”, Annual Reviews in Control, 42, pp.63-81, 2016.

Tinga, T. and Loendersloot R., “Aligning PHM, SHM and CBM by understanding the physical system failure behaviour” in: Second European Conference of the Prognostics and Health Management Society, 2014.

Ton, B., Basten, R., Bolte, J., Braaksma, J., Di Bucchianico, A., van de Calseyde, P., Grooteman, F., Heskes, T., Jansen, N., Teeuw, W., Tinga, T., Stoelinga, M., “PrimaVera: Synergising Predictive Maintenance”, Applied Sciences, 10, 2020.

Wang, B., Zhong, S., Lee, T.-L., Fancey, K.S., Mi, J., “Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review”, Advances in Mechanical Engineering, 12(4), 2020.

West T., Blackburn M. “Is digital thread/digital twin affordable? A systemic assessment of the cost of DoD’s latest Manhattan Project”, Complex adaptive systems, Chicago, USA, 2017.

Wilson J.M., Piya, C., Shin, Y.C., Zhao, F., Ramani, K., “Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis”, Journal of Cleaner Production 80, 2014.

Wright, L., Davidson, S., “How to tell the difference between a model and a digital twin”, Advanced Modeling and Simulation in Engineering Sciences, 7(13), 2020.

Xiao et al., “Fusion model of inductive thermography and ultrasound for nondestructive testing”. Infrared Phys. Technol., 101, 2019.

Content Summary

This lecture is both a short introduction to the recent developments, challenges and opportunities in Aviation Maintenance, Repair and Overhaul (MRO), and also a presentation of the research focal areas and the key waypoints towards smarter and more sustainable MRO.

Innovation and integration have always been key aspects of Aviation. Currently, evolutions in aircraft design, materials and production techniques are ahead of the MRO practices in use. This gap is creating demand for new knowledge to develop and operationalise adaptive, digital and sustainable MRO tools, applicable or integrated in modern aircraft systems and components.

The Aviation Engineering professorship seeks advanced technologies and methodologies to optimize MRO processes and reduce aircraft downtime through practice-oriented research. This research actively contributes to helping aviation develop sustainable processes and is focused on two main topics: data analytics and prognostics to predict the maintenance needs and novel inspection and repair methodologies to improve the maintenance implementation.

Short bio

Konstantinos Stamoulis (b. 1970 in Chios isl., Greece) is Professor of Aviation Engineering at the Amsterdam University of Applied Sciences (AUAS).

He was trained as Aeronautical Engineer and specialized in Applied Mechanics (National Technical University of Athens, Greece) and Materials Science and Engineering (Massachusetts Institute of Technology, US). He finished his PhD in 2008 on *Fatigue of Micromechanical Systems* (University of Thessaly, Greece). He has been involved in teaching and research in various academic programmes and worked as a research assistant at the Technology Laboratory for Advanced Materials and Structures (MIT, US) and at the Laboratory for Strength of Materials and Micromechanics (UTH, Greece).

Konstantinos was formerly a senior officer in the Hellenic Air Force (HAF), where he held various technical and operational appointments in maintenance and engineering organizations from 1993 until 2018. He served as Director of Engineering and Industrial Design at the Air Force Aircraft Depot from 2011 to 2017.

Following his departure from HAF in 2018, Konstantinos joined AUAS as a full-time, associate professor where his areas of interest include advanced maintenance technologies, composites engineering, and data analytics in Aviation Maintenance, Repair and Overhaul (MRO). Since 2020, he has been appointed as full professor at the Faculty of Technology.

He serves as a scientific committee member and keynote speaker in conferences internationally and as a member of the Executive Committee of the Aerospace Network of the Institution of Engineering & Technology (IET).

This book is both a short introduction to the recent developments, challenges and opportunities in Aviation Maintenance, Repair and Overhaul (MRO), and at the same time, a presentation of the research focal areas and the key waypoints towards smarter and more sustainable MRO. Innovation and integration have always been key aspects of Aviation. Currently, evolutions in aircraft design, materials and production techniques are ahead of the MRO practices in use. This gap is creating demand for new knowledge to develop and operationalise adaptive, digital and sustainable MRO tools, applicable or integrated in modern aircraft systems and components.

The Aviation Engineering professorship seeks advanced technologies and methodologies to optimize MRO processes and reduce aircraft downtime through practice-oriented research. This research actively contributes to helping aviation develop sustainable processes and is focused on two main topics: data analytics and prognostics to predict the maintenance needs and novel inspection and repair methodologies to improve the maintenance implementation.

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