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Integrating the maintenance process: A framework to bridge design for maintenance to prescriptive maintenance

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ABSTRACT

Due to the rising concern over the impact of global warming and significant climate changes, the aviation industry is looking for solutions to reduce emissions. To achieve sustainable aviation, a lot of attention is being paid to the development of new aircraft designs but also retrofitting existing aircraft with the electric propulsion system. During the early design phase, the Design for Maintenance (DfM) aspect needs to be considered to facilitate ease of maintenance and safety during the operations. In this paper, the relation and impact of early design considerations on maintenance operations are presented, and a framework integrating prescriptive maintenance and DfM is proposed.

Keywords: Electric Aviation, Design for Maintenance, Aircraft Maintenance, Prescriptive Maintenance, Sustainability.

1. INTRODUCTION

The aviation industry is one of the most important transportation sectors that has a significant impact on the socio-economic development of many countries[1]. However, it is largely dependent on liquid fossil fuels with total energy consumption of up to 5%, resulting in the emission of greenhouse gases[1]. Emissions from the aviation industry, both CO_2 and non-CO_2, have a significant impact on the environment[2]. The aviation industry contributes 12% of the total CO_2 emission from the transportation sector along with SO_2, water vapor, soot, and NO_x which leads to the formation of acid rain and contrail formation[1, 2]. Along with emissions, noise near the airport areas is a challenge as it leads to potential cardiovascular diseases for the people in the close vicinity of the airport[3].

Despite the environmental impact, the aviation industry is expected to grow significantly in the coming years, with an expected annual growth rate of 5%[3][12]. Given the importance of the aviation industry and expected growth in fleet size, there is an urgent need for decarbonization to reduce emissions. These concerns coupled with the depletion of fossil fuels and rising fossil fuels are encouraging the aviation industry to move towards more sustainable solutions. According to studies, the development of bio-fuel coupled with improved aircraft technology, improved and optimized operations, and air traffic management has a greater potential to reduce emissions[4]. However, the design, development, and certification of electric aircraft are also gaining moments due to improved battery technology with higher energy density. Electrification of aircraft enables locally zero-emission, reduction in the overall maintenance cost due to less moving parts in comparison to conventional aircraft, and energy-efficient aircraft [5].

Although electrification of aircraft is gaining traction, there is a knowledge gap in terms of maintenance challenges posed by electric aircrafts and it's interaction with the airport ecosystem [45]. As presented by [6], the aviation market is characterized by very strong competition and rapid changes brought by deregulation, fast technology improvements and industry consolidation. However, despite the competition and costs raise, affordable airfares continue to be expected by passengers [6] resulting in a complex and challenging context for the airliners and as a consequence 34 airlines went out of business in 2021 alone [7]. One more challenge currently faced by the aviation industry is lack of workforce [8,9].

Given the current challenges, airlines and MRO companies that can quickly adapt will take the lead in the market arena. In this context, a new maintenance approach is needed to overcome the sustainability and work force challenges by augmenting current workforce capability and skills, lowering asset life cycle cost specially in terms of energy expenditures, while increasing asset availability: Prescriptive Maintenance (PsM) is this approach. Enabled by the surging Internet of Things (IoT) systems being developed by MROs companies and airliners, PsM is the maintenance philosophy that, through analysis of real time asset and resources data, predictive maintenance assessment and prescriptive analytics, not only provides the best maintenance strategy on what to do, when, who, why, where and how, but also optimizes the asset life cycle cost boosting operation's sustainability.

To address these challenges, it is presented in Section 4 the novel Design for PsM framework (DPMF), an evolution of the Smart Prescriptive Maintenance Framework (SPMF) proposed in the previous works [6] and [15], to bridge the gap between field lessons learned and product development while ensuring operation sustainability, efficiency and asset availability.

2. LITERATURE OVERVIEW

2.1. Significance of Maintenance Repair & Overhaul (MRO) in the aviation industry and challenges

If it is considered that, as pointed out by [14], maintenance repair and overhaul represent 20% of airline total operating costs, maintenance providers are required to constantly lower their cost share and contribute to a more reliable and sustainable aircraft operation. Although the MRO market is forecasted to reach USD 97 billions by 2023, exceeding pre pandemic levels, pressure on maintenance cost is even stronger than before in the post covid environment since – now more than ever – airlines need to keep costs under control if they are to manage the heavy debts incurred during the crisis [13]. Yet at the same time, they must pursue their investments in more recent aircraft with lower fuel consumption and CO_2 emissions levels. Airlines are being pulled in opposite directions by the need to continue modernizing their fleets while simultaneously keeping their cash flow and budgets under tight control. Also, there is the need of fast adaptation to support different airframes to ensure business sustainability. To achieve this, as mentioned by [15], the aviation industry is continuously introducing digital technologies and upgrading its information technology [9] systems to automate the state detection of their assets and derive maintenance decisions. This remark is strengthened by [13] which reports that MRO organizations have turned more intensively on digitalization to gain efficiency, although it is a gigantic challenge due to regulation. Digitalization is expected to stabilize MRO organizations' processes by optimizing operations and workforce productivity, while reducing costs and enhancing the customer experience. This digitalization is mainly focused on predictive maintenance, augmented/virtual reality, drones, exoskeletons, and man-machine collaboration which is promising to make the work of the mechanic faster, safer, and more efficient.

Another challenge airlines and maintenance repair and overhaul (MROs) companies alike are facing is the workforce crisis, as pointed out by [8] and [9]. In fact, more than 500k technicians will be needed in the next 20 years but only 5k were certificated by the FAA in the last couple of years. Demographically, more than 60% of them are 60 years old or older and the whole workforce average age is 53 years old, which is 11 years older than the US workforce median age, meaning that the current aircraft mechanics will retire in the next 10 to 15 years [9]. On top of that, the required skills are changing faster than universities can adjust, being a challenge educating workers fast enough and provide them with skills companies need [10]. All this while the global commercial fleet will grow at an average pace of 5% a year [3][11] and the workforce size at half this pace [12]. Still according to [9], the shortage of labor may drive up maintenance costs for airlines and increase turnaround times for scheduled maintenance; a potentially devastating blow for the industry, as many airlines already struggle to keep profitability at a reasonable level due to low-cost tickets [6]. As indicated previously by [10], the workforce shortage is due in part to an aging global population. But this is far from being the only issue: attracting new talent to the MRO industry is proving to be difficult, in fact, up to 30% of those who finish an aviation maintenance training course end up working in another industry, so competition for talent is also an issue [12]. All in all, in a post covid environment airline and MROs organizations are not able to hire fast enough to keep up with travel demand [13].

2.2. Maintenance concepts overview

In general, maintenance is defined as the combination of all technical and administrative actions, which ensure that a system is in its required functioning state, and it is related to actions such as repairing, replacing, overhauling, inspecting, servicing, adjusting, testing, measuring and detecting faults [18].

Maintenance is classified according to 3 strategies [19]:

1) Management based strategies:

Total Production Maintenance (TPM): it is maintenance activities that are productive and implemented by all employees, from senior management to operators encompassing all organization's department. It has 5 pillars namely, improving equipment effectiveness, improving maintenance equipment and effectiveness, ensure early equipment management and maintenance prevention, provide training to all people involved, involve operators in routine maintenance [19].

Total Life Cycle Cost Strategy (TLC): it is a systemic approach of managing the maintenance of a system from inception to disposal. The Program Manager is the single point of accountability for accomplishing program objectives for TLCSM. Consequently, the PM is responsible for the implementation, management, and/or oversight of activities associated with the system's development, production, fielding, sustainment, and disposal [20].

Reliability Cantered Maintenance (RCM): it has four main pillars, namely, preserve functions, identify failure mode that can defeat the functions, prioritize functions need (via the failure modes), select only applicable and effective preventive maintenance tasks [21].

2) Strategies with no sensing and computing technologies:

Run to failure strategies: it is a maintenance strategy where maintenance is performed after equipment failure. Unlike reactive maintenance, run to failure maintenance is adopted deliberately for some assets to which would be too costly the adoption of a proactive or preventive strategy [18].

Preventive maintenance (PM): it was introduced in the 1950s, after the recognition of the need to prevent failure, PM has been adopted for more complex than those based on the use of hand tools that are usually maintained through run to failure strategy. The basic principle of a PM system is that it involves predetermined maintenance tasks that are derived from machine or equipment functionalities and component lifetimes. Accordingly, tasks are planned to change components before they fail and are scheduled during machine stoppages or shutdown.

Proactive maintenance: all forms of maintenance that include regular functionality checks to either identify upcoming faults or project failures prior to their occurrence are defined to be proactive [14].

3) Strategies with sensing and computing technologies:

Condition bases maintenance (CBM): it is a maintenance strategy that monitors the actual condition of an asset to decide what maintenance needs to be done. Based on the concept of Remaining Useful Life (RUL), CBM dictates that maintenance can only be performed when certain indicators show signs of decreasing performance or upcoming failure. Checking a machine for these indicators may include non-invasive measurements, visual inspection, performance data and scheduled tests. Condition data can then be gathered at certain intervals, or continuously (as it is done when a machine has internal sensors). CBM can be applied to mission critical and non-mission critical assets [23].

Predictive Maintenance: by using the knowledge about degradation mechanism, extends the degradation propagation into the future to project system failures. Basically, this approach combines insights coming from the observation of experienced degradation with anticipated operating loads in the future in order to predict when the asset will fail and support the maintenance decision making process [14].

Prescriptive maintenance: this approach utilizes the information about degradation projections and extend the scope of the maintenance decision making process beyond the asset itself [14] considering maintenance teams, tools, shop repairs capabilities, spare logistics and the operation [6]. By considering the surrounding ecosystem, a PsM strategy allows a level of holistic analysis [28] and optimization of maintenance measures [14] that simply can't be achieved through other maintenance strategies. If predictive maintenance says when the failure will happen, PsM informs what maintenance actions should be taken, when, where, by who, how and why aiming the overall maintenance optimization and ensuring operations performances are met [14][6].

Although PsM is an holistic maintenance strategy [28] and it has been appointed that engineering design improvement based on derived insights from PsM framework should be provided [45], no mentions or implementation propositions about how to influence design are found in the related literature [6][14][15][29]-[43], gap that is addressed in this paper.

2.3. Electric aviation overview

Currently, there is a lot of research and development being carried out by companies and research centers on the electrification of aircraft, improved battery systems, propulsion systems, and aircraft configurations [16]. A study carried out by Hepperle [17] discussed the potentials and limitations of electric aircraft by comparing different propulsion system architectures and proposed modifications to improve the aircraft performance with the available battery technologies. The success of the Electric propulsion system depends on the battery performance, battery safety, power density, power electronics, and light and safe high voltage distribution system [5]. The electric propulsion system can be classified based on the degree of hybridization into All-Electric, Hybrid Electric, and Turboelectric propulsion system [5]. All-electric aircraft draw the required energy for the flight from the batteries and it relies on the weight and the battery storage capacity. Given the lack of energy density, it is suitable for short-distance flights is limited payload capacity. Some examples of All Electric aircraft are Airbus E-fan and Pipistrel Velvis Electro [16]. Hybrid Electric aircraft uses the benefit of integration of turbo engine into the propulsion system and enables various levels of hybridization and configurations such as parallel hybrid, series hybrid, and series/parallel hybrid[5]. A study was carried out by Karpuk. et.al., [16] made an overview of the current developments in the field of electric aviation that included simulation techniques, the effect of Hybrid Electric aircraft from an operational perspective, sizing methodologies, new aircraft architectures, and current technologies.

Along with innovative new design such a Eviation Alice, a 9-seater fully electric aircrafts, research is also being carried out on retrofitting of existing aircrafts by changing the propulsion system. In a study [46], both retrofitting and new design of electric aircraft were analyzed to understand and evaluate the over all performance. Given the number of existing aircrafts, specially in general aviation, retrofitting is a feasible way to proceed. In terms of majority of the hazards, electric aircrafts are comparable to conventional aircraft and it is possible to mitigate them under current regulations [47].

Currently, a lot of attention is paid for the technical aspect and performance characteristics of an electric aircraft and not much work is being carried out on the future maintenance work [45]. In a study [45], maintenance personnel expressed their concerns of the over the maintenance of the high voltage battery and recommended to emphasize on the design for maintainability aspect.

DESIGN FOR MAINTENANCE (DFM) AND ITS INFLUENCE ON THE MAINTENANCE OPERATION

The design of a product influences the asset performance throughout the life cycle and cost effectiveness [24]. The design for Maintenance (DfM) approach helps in optimizing the product performance ad future maintenance efforts. It comprises Supportability, Maintainability, and Reliability. Maintainability is how easily, quickly, and safely an asset can be maintained, reliability of an asset is the ability to perform intended functions without breakdowns for a longer period, and supportability is the ability to perform maintenance with minimum cost and time. DfM influences the availability of the product, which in turn influences cost-effectiveness [24]. DfM must be deployed in the early phases of product development so that it is easier to have an overview of the tools and resources required, the life cycle of the system components used in the system, and also the maintenance time required to keep the system up and running [24]. Mulder et.al., [24] have formulated guidelines to enhance the maintainability, supportability, and reliability of an asset.

DfM plays a crucial role in the maintenance of the asset through the life cycle, it is important to keep the availability at the maximum while keeping the overall life cycle cost low in the aviation industry. System failure is inevitable despite ensuring a higher degree of reliability of an asset, the ability to restore it in an event of failure is crucial. Hence, maintainability is one of the most vital systems design parameters to ensure the availability of a product [25]. Critical maintainability attributes that are related to the maintenance process are simplicity, modularity, standardization, diagnosability, and identification, whereas accessibility, assembly/disassembly, ergonomics, and maintenance safety are mainly related to the maintenance activity [26]. As the maintainability attributes are correlated to the maintenance activity and maintenance procedure, it is important to reflect on an early design stages [26]. In the study [25], need for DfM is laid out with the help of a mind map emphasizing on DfM of electric aircrafts but also on the interaction with airport ecosystem, certification, and maintenance training. In order to improve a design, there must be a feedback based on the maintenance procedure carried out.

3. PROPOSED FRAMEWORK: DESIGN FOR MAINTENANCE AND PRESCRIPTIVE MAINTEANANCE

The main aim of PsM is to understand and identify what is wrong with an asset and provide guidance in performing maintenance actions. This enables an easier and more efficient maintenance process for a given asset. However, PsM has the potential to monitor the maintenance action and collect the data required for design improvement that can future improve the overall maintenance process and reduce the life cycle cost. In this study, a proposition to integrate the PsM framework with the DfM framework (Fig.1) is presented to enable the asset manufacturer to make necessary design improvements to enhance availability and improve safety. The SPMF, introduced in Marques [6], was developed and tested on study case presented in Giacotto [15]. This framework is adapted to assembly line constituted by robots and production machines, an operating environment that requires certain production levels, and a maintenance capability constituted by maintenance workforce, tooling, tribal knowledge, and infrastructure suitable for the implementation of the SPMF. The SPMF is built on three pillars.

1. The system’s Reliability, Availability, Maintainability and Safety (RAMS) factors;
2. The operating environment;
3. The organization’s maintenance capabilities [6].

Time is considered during the maintenance schedule in alignment to de Mello [27] and maintenance cost is considered as objective function according to the model proposed by [28] which takes into account the optimal cost (direct and indirect costs) instead of minimum direct cost. This optimal cost encompasses maintenance direct costs (workforce and material), operational irregularity costs, cost of waste-of-life caused by premature maintenance tasks implementation and sustainability costs which measures CO_2 emissions caused by maintenance [14]. The framework presented in figure 1 was built considering the three SPMF’s domains and an implementation in a business case described by Giacotto [15]:

1. RAMS information is represented by the technical publications, manuals, specs, maintenance plan, and the data gathered from the condition monitoring;
2. The operating environment and requirements are defined by the production demand, robots, tools, and workforce; and
3. The organization’s maintenance capabilities are described by the

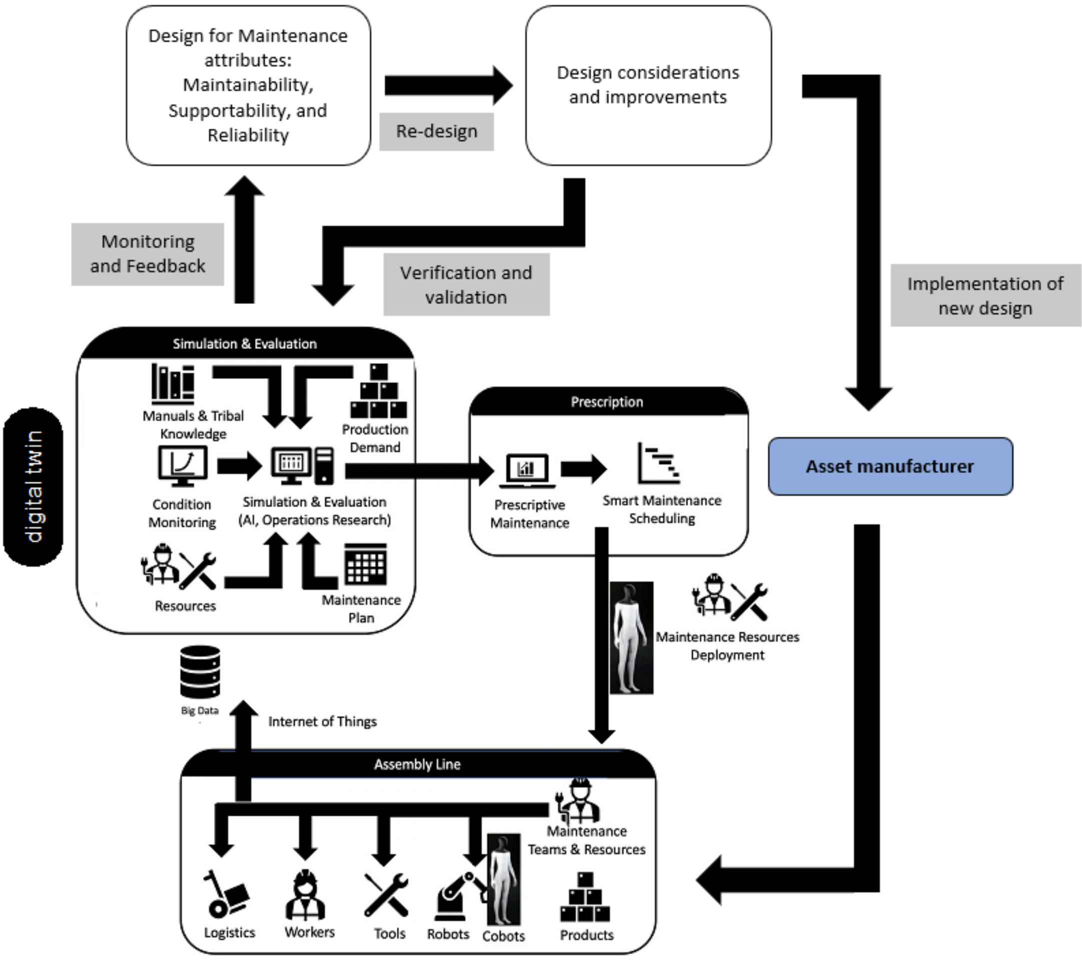

Figure 1: Fig.1. Integration of prescriptive maintenance strategy and Design for Maintenance approach (Design for Prescriptive Maintenance Framework

maintenance resources such as tools, labour available, and maintenance tribal knowledge.

Through IoT infrastructure, real time data is collected about

- Assets' availability, performance, and usage
- Resources availability
- Product quality

Successively, the information is consolidated and used in the simulation and evaluation stage to generate PsM recommendations by optimizing total cost while ensuring operational and maintenance requirements and constraints. The information considered by the simulation algorithm within the SPMF's framework is listed below [15]:

- Maintenance manual and plan
- maintenance team's "tribal" knowledge;
- Equipment condition monitoring to support Prognostics and Health Management, including Remaining Useful Life (RUL) evaluation;
- Available resources such as maintenance labor and tools;
- Production requiremen

Necessary DfM attributes and key performance indicators (KPIs) are monitored using a feedback loop from the framework that helps in formulating design considerations and improvements in the asset. Once the re-design ideas are generated, it is sent back into simulation for verification and validation. This is an iterative process which is carried out until a new design with improved maintainability, reliability, and supportability is generated, which is then implemented by the asset manufacturer. This enables the use of real-life and related scenarios to test the improved design before being implemented. For instance, when a PsM algorithm dictates what must be done in case of a failure, the KPI such as Mean Time To Repair (MTTR) is being monitored and registered. This information is then evaluated against the maintainability attributes and the scope for design improvements is identified. Improved design is then verified and validated using simulations and evaluation tools like digital mock-ups to see if there is a decrease in MTTR. This process is repeated until an optimized MTTR is achieved and the information with the new design is relayed to the asset manufacturer.

4. CONCLUSION

The paper presents the novel Design for PsM Framework (DPMF) which adds design for maintenance processes and techniques to the previously proposed SPMF. The framework addresses the workforce and sustainability challenges adopting total maintenance cost as objective function, maintenance resources and operation requirements as constraints, and using the simulation environment already provided by the SPMF to evaluate the OEM design improvements effects over the maintenance processes, availability and total costs. Once the design modifications are successfully tested and their effects evaluated, the OEM implements them on the assets. As the electric aviation is gaining a lot of traction and lack of knowledge on the future maintenance implies that there is a lot to learn and improve, correlating DfM and PsM. The future work will be focused in developing the experiment in the aeronautical and health industry to evaluate extensibility and viability of the framework.

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