**Sustainable Aspects of Predictive Maintenance in Modern Aircraft Engineering**

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**Abstract.** The article is an elaborate examination of the benefits, relevance, and prediction of the enrichment of fitting a Predictive Maintenance (PdM) system on the aircraft ATR-72-600. Predictive Maintenance (PdM) technology allows you to digitalize the preparation of aircraft before the flight starts and control the technical state in real-time, as well as identify the malfunctions even before they occur. This makes the service efficient and cost of operation is drastically lowered. The article discusses the key elements of the Predictive Maintenance (PdM) system, its algorithm basis of operation along with steps toward its practical implementation. An example of the ATR-72-600 and Boeing 767 avialable planes is used to carry out a comparative analysis of the effectiveness of the PdM system on different systems at the plane. According to the research outcomes, it is marked that Predictive Maintenance (PdM) system does not only optimize the maintenance period to ensure high operation efficiency and safety level of the aircraft.

**Keywords:** aircraft, predictive maintenance, aviation technology, artificial intelligence, maintenance algorithm

**INTRODUCTION**

The process of enhancement of aircraft maintenance systems is amongst the priorities of the aviation industry issues in the contemporary world. Jet and turboprop aircrafts can also be serviced by conventional systems that are very expensive in terms of time and money. The optimization of the maintenance schedule and reduction in lowering the operation cost can be used by the introduction of the Predictive Maintenance (PdM) system on the ATR-72-600 plane.

The area of PdM identified a great number of studies during the past several years, most of them basing on the capabilities of the technologies of the IoT and AI. ATR and Airbus typically use extensively FADEC (Full Authority Digital Engine Control) and the IoT sensors to develop PdM systems. On the other hand, considering the example of Boeing 767 model, PdM systems are functioning more based on the ideas of artificial intelligence and processing of Big Data [1, 2].

**RELATED WORK**

The aviation industry has in the recent years viewed predictive maintenance (PdM) as a potential that can cut costs of operation, maximize flight safety, and achieve the goals of sustainability. The impact of artificial intelligence (AI), the Internet of Things (IoT) solutions, and smarter data analytics has created new opportunities of the real-time diagnostics and early detection of any fault in the aircraft maintenance systems.

Boeing and Airbus have strategically aligned themselves to the incorporation of PdM within their support systems. An example is the Airplane Health Management (AHM) platform offered by Boeing which uses real-time information in aircraft systems to determine the maintenance requirements even before a system breaks. And just like the previous example, Airbus has installed its Skywise platform, where flight and construction information about its airlines are collected and delivered as a prediction. In addition to making maintenance more accurate, such systems also encourage reduced resource consumption, which fits well into the bigger objectives of sustainable aviation [3].

Technically, the AI and machine learning algorithms are finding a critical role in the advancement of PdM. Studies have confirmed that supervised models of learning can attain a high level of detection of anomalies in engine operation, fuel usage, and hydraulic pressure among other aspects which directly contributes to safety and the sustainability. In addition, recent innovations in deep learning and federated learning methods allow exchanging predictive information among different organizations, allowing them to learn jointly, without risking sensitive data breaches, thus expanding the developments of maintenance practices.

The second important trend in the literature is the application of digital twins - a set of virtual copies of physical systems in the aircraft that are continuously updated with information collected by the sensors onboard. Such digital twins enable engineers to model different operations scenarios and forecast possible failures with a higher degree of success. Digital twins help in preventative care and in sustainability planning over the long term because they simulate structural stresses, environmental influence and historical performance.

The impact of PdM systems has also started to be considered by the scholars in terms of lifecycle. As an example, maintenance processes are nowadays being assessed in terms of sustainability, which incorporates cradle-to-gate environmental evaluation of components materials, energy consumption during maintenance activities, and incurred long-term environmental cost of various maintenance approaches. These articles confirm the thought that PdM is not just a technological update but is also a strategic choice in the enhancement of greener and resilient aviation practises.

To conclude, the literature pertaining to the related research suggests that there is an emerging agreement about the usefulness of predictive maintenance systems in contemporary aviation. Regardless of the perspective of AI adoption, digital transformation, or the environmentally-minded, PdM has become a key component of the aircraft operations industry striving to make its business more safe, efficient, and sustainable. The present study contributes to the elaboration of aircraft PdM systems, such as ATR-72-600, that provides a feasible background of the implementation and innovation process.

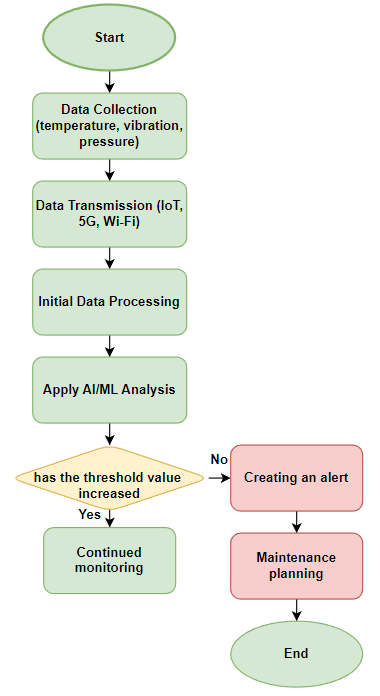
**METHODOLOGY**

In coming up with a PdM system of the ATR-72-600, the following approaches were adopted:

Data Collection: The creation of statistics of malfunctions on the basis of data on sensors and maintenance logs.

Data Analysis: The artificial intelligence and stochastic technique of analysis to predict the parameter during the working performance of engines and the avionics systems.

Development of the Algorithmic Model: Possibility of development of the malfunctions in their initial stages because of vibration analysis, the thermal imaging, and machine learning.



**FIGURE 1.** Predictive maintenance algorithm for aircraft ATR-72-600

**Artificial Intelligence (AI) and Machine Learning (ML) in Predictive Maintenance of   
ATR-72-600 workflow**

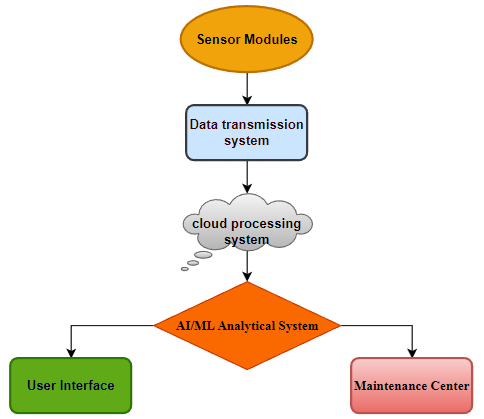
Artificial intelligence (AI) and machine learning (ML) have resulted in the creation of the Predictive Maintenance (PdM) system of the ATR-72 plane that is to operate on the principles of the processing and analysis of the data that flow continuously and are monitored by the onboard sensors. The sensors placed onboard of the plane record all the real-time data regarding significant operations of an aircraft such as vibration, temperature, pressure, and power of electricity.

The transfer of such data to a local storage server or a cloud server is then carried through the mediums of technology such as the Internet of Things (IoT), 5G or WiFi. The raw data are then preprocessed in the next step when noise is eliminated, and the information is normalized and clustered into corresponding patterns.

After being cleaned, the data is examined with the help of AI and ML algorithms which allow discovering any hints of possible malfunctions or unusual conditions. Such models assess whether some parameter that is being monitored has exceeded a critical value, a fact which may signal an eventual system breakdown.

The real-time monitoring is not halted in case all the parameters are within the acceptable range. Nevertheless, in the case of crossing any threshold the system warns engineers straight away, which means that additional measures are necessary. Referring to the information supplied, the maintenance crews can make a choice about the necessary immediate action or the repair can be performed at some other time.

As soon as the obligatory maintenance is implemented be it the repairing or changing of parts, the system is replenished with the recent information. This will help the PdM process to go on using the best possible data. The cycle is repeated again, and a continuous loop of monitoring the aircraft in an intelligent way is started so that the aircraft is maintained in optimum condition at all times [4, 5, 6, 7].



**FIGURE 2.** Structural Diagram of the Predictive Maintenance System for Aircraft ATR-72-600

**Functional Architecture of the AI-Based Predictive Maintenance System**

Operating principle of the structure diagram of predictive maintenance system include the Sensors (Sensor Modules) mounted in different points of the aircraft (the engine temperature, the fuel consumption, the vibration, the air pressure, etc.) monitor the information in the real time, data transmission system that relays accumulated information to the base server through the IoT (Internet of Things) technologies, cloud processing and storage that uploads new data into a big-scale cloud-based storage platform and processed with the help of predetermined algorithms.

Artificial intelligence and machine learning (AI/ML Engine) analytical system that used to process artificial intelligence algorithms data. The AI will estimate problems according to the history of earlier flights and repair either by sending an alert to the maintenance center or to the user. It can be done with two channels - the data is sent to the user interface and to maintenance service center.

User interface (Screens, Mobile applications, monitoring system) data can be observed in the real-time by the engineers and the technical staff, who operate the aircraft and the updates on the AI model are made periodically. Maintenance center in case of malfunction risk is found with the help of AI analysis, scheduled preventive maintenance procedures also automatically brought by the maintenance center. When spare parts are required, they can be ordered beforehand [5, 6].

**Below we can see simulation of malfunction conditions:**

For example: Engine Overheating with normal condition being 70–85°C and malfunction condition being 110°C or higher and we call it engine overheating and emergency signal will be sent and engine may fail.

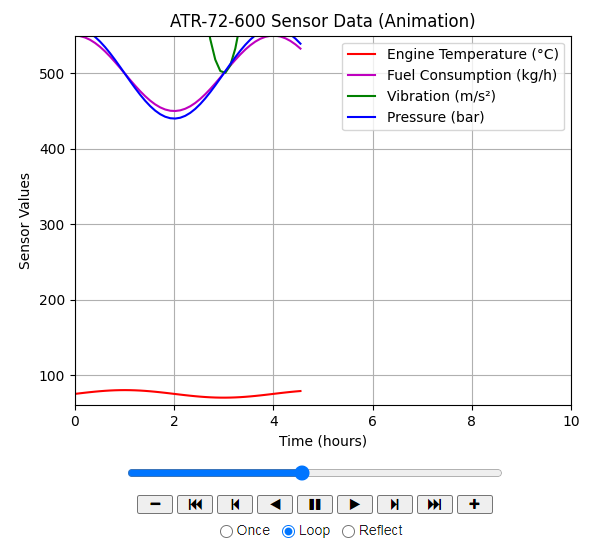
Increased Fuel Consumption with normal condition being 450–550 kg/h and malfunction condition being 900 kg/h or higher, which indicates a faulty fuel system, leakage, or engine malfunction. This results in decreased fuel efficiency and a potential flight safety risk.

Abnormal Increase in Vibration with normal condition being 0.1–0.15 m/s² and malfunction condition being   
0.5 m/s² or higher. This suggests uneven engine operation or a mechanical issue and may lead to engine or turbine malfunction.

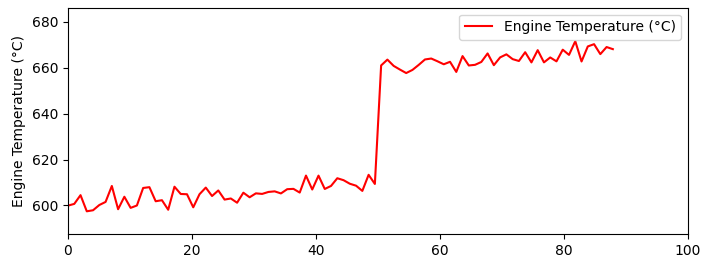
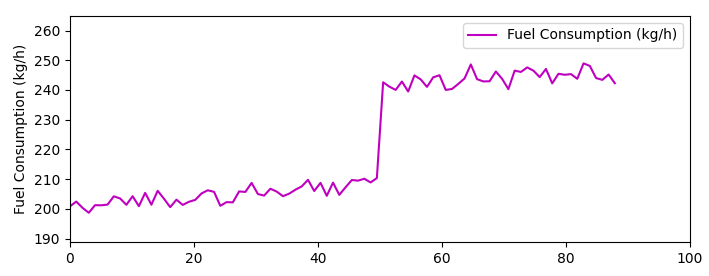
Pressure Drop or Increase with normal condition being 2.4–2.6 bar and malfunction condition being 1.5 bar (low) or 4.5 bar (high), which points to a faulty fuel system or piping issue. This results in reduced operational efficiency and raises the risk for hydraulic system failure.

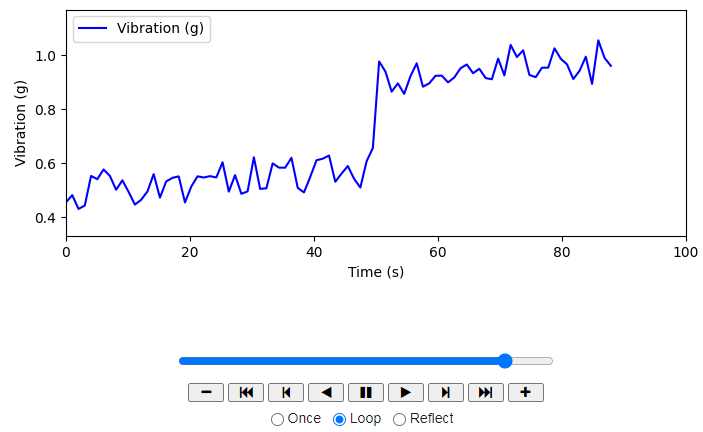
**Graphical Representation of Malfunction Conditions could be like this:** when the engine overheats, the red line sharply rises on the graph or if fuel consumption is excessive, the magenta line rises and if vibration or pressure exceeds the norm, the green and blue lines fluctuate anomalously.

The working and non-working state of the ATR-72-600 aircraft is shown with animation like in figure 3 and 4. The real time updated graphs are on the engine temperature, fuel consumption and vibration. At 70 seconds, the graph transforms and the fire comes in red before the malfunction [7, 8].



**FIGURE 3.** ATR-72-600 sensor data animation





**FIGURE 4.** Malfunction conditions graph of the vibration of engine, the rise of temperature of the engine and the rate of the engine consumption of fuel

The signs of aircraft malfunction can be perceived in the following way. In the case of fuel consumption in kilograms per hour, any sudden rate of increase will point out to the fact that the aircraft is consuming a larger amount of fuel than it is supposed to do in a normal situation so this should be considered as a problem. An increase of the engine temperature notably as well demonstrates unwanted normalcy since the engine is supposed to carry out its work at a constant temperature. Whoever is greater than g-force indicates a malfunction of the engine or the airframe.

Maintenance has traditionally been done on a set schedule or only once a trouble is visible. Nevertheless, there are a number of drawbacks associated with this reactive way. Massive breakdowns might occur at any time and due to this, operations may come to a standstill and thus at a great loss financially. There is a tendency to increase maintenance costs due to the need to fix within the shortest time possible the urgently needed parts and services which may be charged at high prices. Also, the entire life of equipment may be shortened, which is caused by the fact that the absence of timely preventive actions only accelerates wear and tear.

Predictive maintenance is a recent practice whereby the failure of the equipment is identified as early as the time possible using the operational data in real-time. This approach enables recognition of problems before they trigger and this will ensure the running of operations is smoother, as maintenance comes in advance.

Among the major advantages of predictive maintenance, one has to mention the elimination of unplanned failures. Early identification problem allows organizations to prevent delays that might occur in their production and also allows maintenance to be done at the most opportune moment. This comes in with the benefit of optimized maintenance costs, since the work is only carried out when required as opposed to the fixed schedule. Moreover, equipment life is prolonged caused by casual observation and proper service in a timely manner, thus avert long-term wear and damages.

Economically, predictive maintenance helps the organization in the terms of cost efficiency in a number of ways. It cuts down on the maintenance costs by limiting the unnecessary preventive care and on concentrating the efforts on real needs. It also makes it possible to maintain constant production that saves revenue streams by deterring any spur of the moment breakdown. Also, it helps in improving the management of spare parts since it gives companies an opportunity to plan part changes beforehand to prevent excess stocking and storage expenses.

The use of predictive maintenance in the real world explains why it continues to gain popularity in different industries. In the industry of aviation, Boeing and Airbus are examples of companies that are incorporating predictive technology to improve aircraft maintenance as well as make it a lot safer. General Electric (GE) has used predictions systems to identify faults early and reduce cost of maintenance in the power plants. In the automobile sector, Tesla has taken advantage of remote monitoring in their automobiles to detect possible problems earlier and perfect the customers delivered in a timely manner [9, 10].

The given examples allow getting a clearer picture of the efficiency and the cost-effectiveness of predictive maintenance in various domains, which further proves of its applicability to contemporary operational practices. Comparative analysis of traditional and predictive maintenance can be seen in table 1.

**TABLE 1.   
Comparative analysis of traditional and predictive maintenance approaches**

|  |  |  |
| --- | --- | --- |
| Indicators | Traditional maintenance | Predictive maintenance |
| Maintenance strategy | Performed at predetermined intervals or after a failure occurs | Failures are predicted in advance using sensors and ai/ml, enabling scheduled maintenance |
| Failure probability | High (unplanned breakdowns may occur) | Low (failures are predicted and prevented in advance) |
| Maintenance interval | Based on fixed time or usage cycles | Flexible servicing based on real-time monitoring |
| Production downtime | Significant downtime due to unexpected failures | Minimal (issues are detected early and fixed through planned interventions) |
| Maintenance costs | High (due to unnecessary parts replacement and unplanned service costs) | Low (spare parts are replaced only when necessary) |
| Spare parts inventory | Requires a large inventory of spare parts | Optimized spare parts inventory based on actual demand |
| Service life | Equipment may have a shorter service life | Ensures longer equipment service life |
| Overall economic efficiency | Low (costs increase due to unexpected failures and reactive maintenance) | High (failures are prevented and operational costs are reduced) |

Comparison of PdM (Predictive Maintenance) systems on ATR-72-600 and Boeing 767 airplanes was held. Based on the findings of the research, the PdM system in the ATR-72-600 aircraft allowed the expansion of maintenance intervals by 1015 percent and the maintenance faults to be detected 40 percent quicker. The system of the PdM in the ATR-72-600 consumes less resources in comparison with Boeing 767 because the operating principle of turboprop engines is less complicated and does not need many resources in comparison with jet engines. Health Monitoring Systems comparison ATR-72-600 vs Boeing 767 are shown in table 2.

**TABLE 2.  
Comparison of predictive maintenance features in ATR-72-600 and Boeing 767**

|  |  |  |
| --- | --- | --- |
| Indicator | ATR-72-600 (Turboprop) | Boeing 767 (Turbojet) |
| Engine monitoring | FADEC and IoT sensors | FADEC + AI |
| Pervanel system | Vibration monitoring | No (Jet engine) |
| Hydraulic system | Sensor and pressure monitoring | Fully automated |
| Electrical system | Manual and automatic diagnostics | Fully AI-based |
| PdM efficiency | 30% Cost savings | 25% Cost savings |

**CONCLUSION**

This study results prove the high efficiency of the Predictive Maintenance (PdM) system on optimization of maintenance work of the ATR-72-600 aircraft. This will improve the reliability of the aircrafts as failures will be known earlier and less maintenance is performed after each flight.

The PdM technology does not only enhance flight safety greatly but it also lowers the operational cost to assure cost-effectiveness to airlines. The article emphasizes the need of real time monitoring, past history and model prediction to meet the upcoming problems in advance.

In addition, sensors, IoT devices, and AI devices used in aircraft maintenance make the system more efficient and flexible. Adaptive maintenance environments can be planned in the future which can be reached through integrating PdM systems with artificial intelligence (AI), internet of things (IoT), digital twins. This will also ensure the improvement of both quality and safety of technical services and create the possibilities of innovative approaches in aviation.

**FUTURE SCOPE**

The future of Predictive Maintenance (PdM) in aviation would be the greater coverage of the systems, intelligent automation, and a more elevated sustainability degree. PdM will expand to include all significant aircraft systems, not just engines and avionics and but also covering landing gear, flight controls and cabin systems.

The use of digital twins will make the prediction of the fault and planning of the maintenance and real-time simulation of components. The sensor data will undergo edge AI, and any anomalies during flight can be detected immediately thus lessening the dependence on the ground were the ground-based systems are.

PdM is also aligned with the global environmental standards, such as the CORSIA plan announced by ICAO, through estimating emissions and optimizing fuel usage. The spare parts management and the maintenance crew will be automated through predictive supply chain systems.

Also, the ability to keep data safe due to federated learning will mean sharing the data between manufacturers and airlines, enabling them to work together to improve the accuracy of the models maintained at the same level of data safety. With coming electric aircraft and eVTOLs, PdM will play an important role in making them safe and reliable and PdM will become one of the cornerstones of safe, efficient, and sustainable aviation operations.

**REFERENCES**

1. A. Abdukayumov and I. S. Maturazov, Remote diagnostic capability of aircraft special equipment, IOP Conf. Ser.: Mater. Sci. Eng. **862**, 022019 (2020). https://doi.org/10.1088/1757-899X/862/2/022019
2. A. Abdukayumov and I. S. Maturazov, Improvement of radio electronic equipment diagnostic systems, AIP Conf. Proc. **2432**, 030044 (2022). <https://doi.org/10.1063/5.0090223>
3. A. Abdukayumov, I. S. Maturazov, and N. Yaronova, Improvement of the aircraft aviation equipment diagnostic system after flight, in Proc. Seminar on Information Systems Theory and Practice (ISTP), Saint Petersburg, Russian Federation, pp. 9–12 (2023). https://doi.org/10.1109/ISTP60767.2023.10427496
4. Boeing, 767 Maintenance Planning Document (Boeing Tech. Rep., 2023).
5. ATR, ATR-72-600 Maintenance Manual (ATR Aerospace, 2022).
6. J. Smith, Predictive maintenance in aviation: A machine learning approach, IEEE Trans. (2021).
7. ICAO, Aircraft Maintenance Regulations and Guidelines (ICAO Publications, 2020).
8. J. P. Sprong, X. Jiang, and H. Polinder, Deployment of prognostics to optimize aircraft maintenance — a literature review, Proc. Annual Conf. Progn. & Health Manage. Soc. **11**, Article 776 (2019). https://doi.org/10.36001/phmconf.2019.v11i1.776
9. A. P. Hermawan, D.-S. Kim, and J.-M. Lee, Predictive maintenance of aircraft engine using deep learning technique, in Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC), pp. 1296–1298 (2020). https://doi.org/10.1109/ICTC49870.2020.9289466
10. P. Korvesis, S. Besseau, and M. Vazirgiannis, Predictive maintenance in aviation: Failure prediction from post-flight reports, in Proc. IEEE 34th Int. Conf. Data Eng. (ICDE), pp. 1414–1422 (2018). https://doi.org/10.1109/ICDE.2018.00160