



EMBEDDED SENSORS FOR AIRCRAFT PREDICTIVE MAINTENANCE: SHM SYSTEM INTEGRATION & TRADE-OFF ANALYSIS

Vageesha Sharma M¹, Pranav Jha², V. Samanyusree³, Arundhati Sharma⁴, Smrati Maheshwari⁴, Dr. Mamatha G S⁵

¹Department of Aerospace Engineering, R. V. College of Engineering, Mysore Rd,
RV Vaidyanatan, Post, Bengaluru, Karnataka 560059

²Department of Electronics and Telecommunication Engineering, R. V. College of Engineering, Mysore Rd, RV
Vidyaniketan, Post, Bengaluru, Karnataka 560059.

³Department of Electronics and Communication Engineering, R. V. College of Engineering, Mysore Rd, RV Vidyaniketan,
Post, Bengaluru, Karnataka 560059.

⁴Department of Mechanical Engineering, R. V. College of Engineering, Mysore Rd,
RV Vidyaniketan, Post, Bengaluru, Karnataka 560059.

⁵Department of Information Science and Engineering, R. V. College of Engineering, Mysore Rd,
RV Vidyaniketan, Post, Bengaluru, Karnataka 560059.

Abstract

Structural Health Monitoring (SHM) technology is revolutionizing the aerospace industry by enhancing the evaluation of aircraft structural integrity. This research explores the integration of embedded sensor-based Non-Destructive Testing (NDT) systems into aging aircraft structures to automate inspections and enhance predictive maintenance strategies. The primary goal is to improve safety, reliability, and cost-effectiveness in the civil aviation sector. Many incidents and accidents occur annually due to inadequate maintenance, leading to higher insurance costs, unscheduled maintenance, disrupted supply chains, and reduced operational efficiency. This study employs mathematical models, such as Poisson's distribution, in conjunction with real-time monitoring using embedded sensors like fibre optic (Fibre Bragg Grating optic method) and piezoelectric sensors to improve the prediction of unscheduled maintenance. A proof of concept is demonstrated using a case study. Future work aims to integrate the mathematical model with real-time monitoring algorithms to enhance the prediction of unscheduled maintenance and perform a cost-benefit analysis.

Keywords: Structural Health Monitoring (SHM), Predictive Maintenance, Poisson's distribution, Fiber Bragg Gratings (FBG), Real Time Monitoring.

1. Introduction

Aviation safety engineering depends immensely on the aircraft maintenance, older aircrafts still in service incur a lot of untimely issues which prove to be detrimental to the smooth operations might even lead to accidents endangering the safety of the passengers and crew on board, if any issue was to crop up in the middle of the flight. The rite of passage for any profit generating company is to focus its R&D on predictive maintenance scheduling to ensure that a complete overhaul of components which were

otherwise salvageable does not arise frequently, to prevent the unnecessary wastage of resources. Predictive maintenance helps in determining the appropriate time for reaction to a possible detrimental outcome in the near future. This provides a huge save on the various costs incurred and the reduction of the flight's downtime which were practically uncalled for, it calls for the development of an algorithm which would take into account existing cases of failure, keeping the root causes from the frequency of occurrence, add upon it with the existing working conditions of the flight such as temperature, pressure and various elements and its effects on the structure and predict a duration close to the date of failure, the general accepted date for predictive maintenance in any industry is taken as 20 ± 2 days. The main objective is to identify and repair unexpected issues before the hangar visits to ensure complete safety and reliability of the aircraft system otherwise may lead to accidents, fatal or not.

The Airbus A380 although no longer in production is still the largest commercial aircraft in use with a total capacity of more than 500 passengers, cases have happened due to fatigue cracks, internal corrosion, fatigue cracking on the door and disc failure during flight. Although none of the cases were detrimental to life, they can prove to be fatal if failed to be detected further. On 20th May, 2017, an Airbus A380 reported an engine shutdown during flight and had to return back to Los Angeles Airport from which it departed. The cause was determined to be Internal corrosion of low-pressure turbine stage 2 blades resulted in fatigue failure and separation of blade debris and downstream damage through the engine. The corrosion resulted from chemical residue associated with the cleaning procedure, in the hollow blades from cleaning operations at the last service (July 2015). Since the publication of the report, 5 other engines had already been removed from operation fearing the same results over unchecked usage, causing a huge loss of resources both monetary and material wise.

An A380 on 30th September, 2017 had a complete engine failure en route while flying from Paris to Los Angeles had to divert to Goose Bay, Canada. The failure resulted from the progression of a crack origin of which was found to be in the micro-texture zone or the macro zone, engine number no. 4 was damaged; the major part of the fan hub, the majority of the fan blades, the inlet cone, the air inlet (over 2.5 m) and the right and left engine cowlings were missing. As a result, the wing suffered deformation, from the contact due to the various parts that came apart from the engine. The flight had been in operation for 27,184 hours on the date of the accident. While the particular engine had been in operation for 30,769 hours since the last inspection, which proved to be a long stretch from the prescribed date of maintenance as given by the manufacturer.

January 4, 2014, Airbus A380 from Singapore suffered a low of cabin pressure due to cracks present in the door 3L, the skin of the door was found torn and bent outwards. The root cause of door failure was traced to a crack passing through a number of rivet holes on the door skin. The crack was probably induced by high cycle fatigue under varying amplitude loading caused by fluttering of the Batch 1 cover plate (CP) that was initially installed on the aircraft. The replacement of the Batch 1 CP by a stiffer Batch 3 CP could not prevent further propagation of the crack.



Figure 1- Flowchart of the predictive model

The above mentioned and various cases were taken into consideration to understand the various issues that may crop up during the flight which could have been prevented by predictive maintenance. As the name suggests, companies try to prevent major damages by predicting the number of cycles a particular component can run before requiring any maintenance, being the go to commercial practice, there are

still certain cases that arise due to shortcomings of the method in use or human error, hence a real time monitoring system is beneficial for the long running aircrafts such that a particular problem can be focused upon and corrected without putting the entire structure under the microscope, saving money and time.

2. Aircraft Maintenance

Aircraft maintenance is the planning and scheduling of the available resources, such as spare parts, operations like inspection, disassembly and assembly to be performed on the aircraft and the utilization of available labour to the to minimise the flight's downtime and maximise profit. The current model accounts for only 50% of the heavy maintenance activity to planned prior while the other 50% is unplanned maintenance [1]. Unplanned maintenance are issues which do not come up during general inspection and may crop up during the use of the aircraft, resulting in accidents.

2.1 A380 - Scheduled Maintenance

An industry-wide new standard has been established by the A380. Since going into service, the venerable A380 has completed over 800,000 flights with over 300 million passengers. On December 12, 2006, the A380 was granted joint Type Certification by the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA). Airbus has asserted that although manufacturing of the A380 is halted, the aircraft will still be in service for many years to come, and that it will continue to offer full support to A380 operators and their fleets. [2] Appropriate maintenance plans and scheduling procedures can maximise fleet availability and optimise maintenance resources while ensuring the aircraft's airworthiness. Aircraft manufacturers establish maintenance requirements to verify that the aircraft is in compliance with the regulations outlined in "Instructions for Continued Airworthiness." In practice, for a given aircraft programme several documents are established, the primary ones being the Airworthiness Limitation Section (ALS) and the Maintenance Review Board Report (MRBR). Together they are combined into MPD (Maintenance Planning Document), a non-formal document and a compilation of maintenance requirements based on airlines. The latest edition i.e. revision 14 of MPD for Airbus A380 escalated from 24MO (Month) base check to 36MO base checks. Actually, there are three basic reasons why a maintenance programme revision might occur: Modifications to aircraft configuration; Regulations; Feedback from in-service experiences. Initial intervals for the MRBR are frequently rather conservative. Based on the analysis of in-service input, there is a good chance that intervals can be optimised in a way that benefits the operator. The majority of manufacturers have been successful in increasing task intervals many times, which has improved the effectiveness of operator maintenance programmes. The manufacturer gathers both scheduled and unscheduled data from various operator environments, aircraft utilisation, aircraft design, aircraft age, etc. in order to optimise maintenance programme intervals. Table 1 represents the checks required based on 3 major sections: Structure, Zonal and System. [3]

A380 utilizes C1, C2, C3, C4, C5, and C6 instead of letter checks. The A380's architecture maximizes the efficiency of its maintenance programme intervals. The MPD's revision 14 calls for increasing the frequency of a particular C check task from 24 months or 12,000 FH (Flying Hours) to 36 months or 18,000 FH This will prevent one aircraft grounding and one C check every six years. There will only be four checks mainly C1, C2 C3 & C4 as observed in Table 2 in the cycle and two base checks rather than three throughout the 72-month period.

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& TRADE-OFF ANALYSIS**

Table 1- GVI: General Visual Inspection, DET: Detailed Inspection, SDI: Special Detailed Inspection, CHK: Check, SVC: Servicing, VCK: Visual Check, LUB: Lubrication, FNC: Functional Check, OPC Operational Check, DIS: Discard.

Task Codes	System	Structures	Zonal
GVI	140	113	191
DET	109	505	NA
SDI	23	260	NA
CHK	1	NA	NA
SVC	12	NA	NA
VCK	42	NA	NA
LUB	24	NA	NA
FNC	68	NA	NA
OPC	199	NA	NA
RST	73	NA	NA
DIS	57	NA	NA
Total Tasks	748	878	191

Table 2- Airframe, EN: Engine, NDT: Non-Destructive Testing, AV: Avionics, CL: Cleaning, LU: Lubrication, EL: Electrics, RA: Radio and Communications, UT: Utilities

Skill Codes	System Function	Structures Section	Zonal Section
AF	390	571	175
EN	122	49	16
NDT	14	258	NA
AV	63	NA	NA
CL	37	NA	NA
LUB	17	NA	NA
EL	95	NA	NA
RA	6	NA	NA
UT	5	NA	NA
Total Tasks	748	878	191

Table 3- Scheduled checks based on flying hours and flying cycles

C Check	Check Interval MO	MPD (FH)	FH per average Utilisation	Cycle/Utilisation
1C	36	18000	13500 – 15750	1650
2C	72	36000	127000 – 31500	3300
3C	108	54000	40500 – 47250	4950
4C	144	72000	54000 – 63000	6600

Currently, most A380s are now impending towards their first 12 YE(Year) checks. The checks aim at landing gear modifications, alterations to the layout and design of the cabin, modifications to the components of the reliability programme, repainting of the aircraft, and, if necessary, work packages for the transfer of the aircraft to a new operator at the conclusion of its lease. These checks usually exceed 75000MH (Machine Hours). The key progress for the A380 maintenance programme is the shift to a 36MO base inspection cycle, which will significantly lower maintenance costs. It is unprecedented for two checks from a base check cycle to be omitted in just one MPD revision. The MPD of the A380 is at an intriguing stage in its lifecycle, considering that it is currently pushing through the 12-year heavy check milestone.

3. Structural Health Monitoring

Structural health monitoring makes use of non-destructive testing methods to inspect the cases of the aircraft and make a detailed evaluation of the need for any preventive maintenance that may be required for a particular model. The contemporary practices use various sensors such as comparative vacuum monitoring (CVM) sensors, piezoelectric sensor arrays, fibre optic sensor for composite material used in aircrafts, etc. The results are spelled out in a go no-go form so that misinterpretation or human error is cancelled out of the equation.

The concurrent SHM models make use of integrated sensors in the initial phase to monitor strain, temperature, etc. The commissions to be carried out for the implementation of SHM for damage detection is still in its infancy, the following are the fallibilities of the system that nevertheless require ongoing research on the viability and cost effectiveness of its integration in the existing flight control system. With SHM, unnecessary disassembly and reassembly of undamaged structures could thus be avoided. It has also been suggested that a continuous load and damage monitoring of the structure can facilitate weight reduction by assuming effectively shorter inspection intervals when mentioning fatigue-prone structures, thus designing for optimum weight, rather than solely focusing on functionality. Among the main motivations to increase life-safety, the occurrence of fatigue, delamination, debonding, or corrosion damages can be detected and distinguished at an early stage. Possibly, the introduction of SHM can mitigate safety concerns when using novel materials in the aircraft structure, about limited experience regarding long-term operational use, as their condition and degradation will be monitored with SHM. Finally, human error during aircraft inspection can be reduced.[6] The article hence focuses on SHM techniques that can incorporated within aircrafts like A380.

3.1 SHM System in A380

The detection of the onset of damages and overload conditions is the main purpose of the additional of

a sensorial system. The advantages of adding a sensory capability provided are an integrated damage detection system which removes the need of periodic preventive maintenance inspections, structure itself notifies the need of maintenance in a particular region and time frame saving excess costs that would be incurred otherwise. The factor of safety is greatly increased by the early detection of damage. The difficulties of accessing allows only for general annual inspections, and the fact that small local defects, such as local changes in the composition of the adhesive, may initiate a crack which grows as the machine continues in operation as mentioned above in the case of flight accidents in the introduction compels the design to be very conservative with material properties. If there were a system that automatically detects the onset of damage, stopping the machine to repair, it would allow a design much closer to the real strength of the structure.

3.2 Sensors

At present the typical sensors widely used in this field include fibre optic sensors, piezoelectric sensors, long distance wireless sensors and MEMS sensors. The widely accepted sensors for automated SHM models used are FOS (Fibre Optic Sensor) and Piezoelectric Sensor (PS) to make a detailed discussion on their implementation for in flight SHM, as the manual work performed on the aircraft accounts for 10% of the airlines operating costs [6].

3.2.1 SHM using Piezoelectric Sensors

Piezoelectric sensors are based on piezoceramic materials. Bonded on structures they are suitable for generating or measuring mechanical strain depending on the applied electric field. Changes of the electric field lead to changes in the mechanical strains, thus causing wave propagation. In solid bodies so called Lamb Waves can be excited. They propagate along great distances and are reflected by damages. By the comparison of the excitation of the wave and the corresponding reflection suitable information on damage in materials can be obtained. SHM using Lamb Wave compares the wave propagation before and after structural damage. In an ideal case it results into three types of information: 1. The difference between the original and the actual condition, which can be taken as a damage value, 2. the localisation of the damage, 3. and the specification of the damage concerning type (crack, delamination), dimension, type (fatigue, impact), direction, growth and so on. [8]

3.2.2 SHM using Fibre Optical Sensors

Fibre Bragg Gratings (FBG) are optical interference filters which are inscribed into optical waveguides and which reflect a defined wavelength of the incident light. The part of the optical waveguide which includes the FBG has to be bonded to the structure. The behaviour of a fibre-optic cable with embedded Bragg gratings is inversely proportional to its length. These kinds of sensors can be introduced in different ways that couple mechanical strain, temperature, speed increase, or strain to the extension felt along the fibre utilizing a focal cross examination unit. The elongation is measured by using laser light that passes through the fibre. A single fibre-optic cable can contain thousands of sensors in series due to the ease with which multiple gratings can be written into a length of optical fibre. These signs can be decoded all the while utilizing optical recurrence area reflectometry (OFDR) methods, delivering exact strain estimations down to 1 macrostrain goal and complete insusceptibility to electromagnetic clamour. The strain data can be utilized straightforwardly or be present handled on acquire shape data, contingent upon the application. The sensor components, situated at similarly separated stretches along the fibre-optic link, return frequency encoded data about their lengthening at a specific area. In areas quite compelling, the fibre can be directed close to pressure focus highlights and through areas of greatest anticipated pressure. Loops can be attached to a single fibre to create strain rosettes in any orientation or location. [9]

A380 involves a lot of area which needs to be covered for predictive maintenance, regions such Wings, Fuselage, Tail section, Landing gear control surfaces are most vulnerable for any damage, fibre bragg grating is one of the best options available currently for real time predictive maintenance. Each fibre can be individually configured for spatial resolution, sensor locations, and signal filtering.

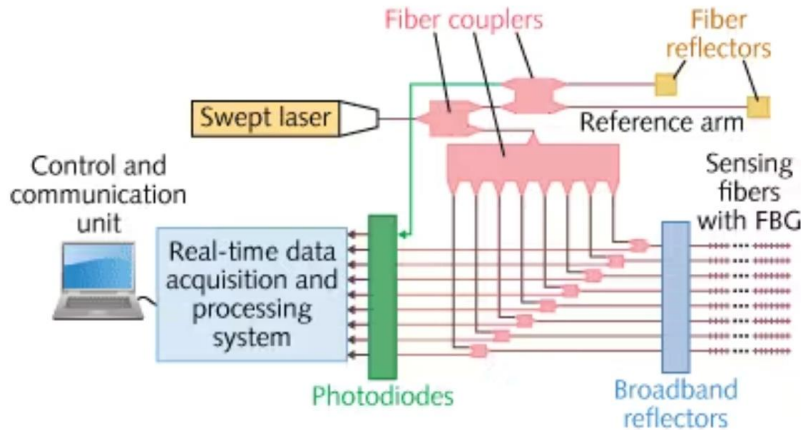


Figure 2- Setup of FBG structural integrity sensing system [9]

Many advantages and disadvantages can be found in literature. FOS are insensitive to electromagnetic disturbance, difference of potential, humidity and are suitable for use in explosive areas like fuel tanks. The fibre, which works as sensor as well as signal transmission medium, allows inscribing numerous gratings on different positions. This reduces the effort of installation and associated cost compared to an application using electric strain gauges. The fatigue behaviour of FOS is much better than that of DMS. FOS can resist strains up to a level of $10000\mu\text{m}/\text{m}$. The disadvantages of FOS are their temperature sensitivity, which need special compensation methods. Pressure loads and shear forces can cause birefringence and measurement errors caused by additional signal reflection peaks. FOS are used for aerospace applications as well as in the energy industry, in medical technology and civil engineering, for example for the monitoring of bridges, buildings and dams. Glisic presents many applications. Müller uses FOS for structural monitoring and displacement field estimations. Figure 2 shows experimental results to observe PZT and FBG sensors in SHM system.

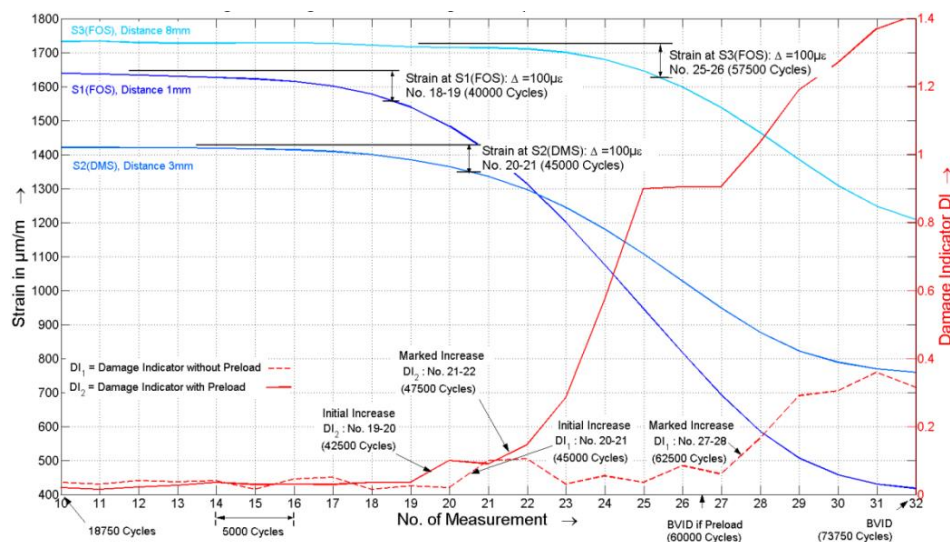


Figure 3- Data results from incorporating FBG and PZT [11]

3.2.3 Economic Impact

The automation of costly manual processes in maintenance, repair, and overhaul (MRO) using health

monitoring systems (HMS) can play an important role: most of the work is performed manually and accounts for approximately 10% of airline operating costs, and approximately 30% of the MRO costs are driven by structural MRO. Chenet al.¹² look specifically into the influence of SHM on scheduled maintenance, and estimate that a reduction of 33% in maintenance costs may be achieved over scheduled maintenance for a composite wing. In contrast, Pattabhiraman et al. states that SHM could incur a cost increase of \$3.5 M due to the weight penalty, but on the other hand, CBM could lead to a \$12M benefit over scheduled maintenance, leading to a net benefit of approximately \$8M over the lifetime of an aircraft.[11]

For this reason, the mechanization of non-destructive testing (NDT) via structural health monitoring (SHM) with sensors attached to or embedded in the structure increases the effectiveness and reduces the costs in a structural maintenance program. The measured parameters, combined with data analytics or artificial intelligence (AI) is used to detect faults at an early stage and predict imminent failures. SHM systems (SHM) promise various economic and safety advantages. One of the principal economic profits arises from shifting scheduled maintenance to condition based maintenance.

According to the technological level of the SHM solution, the sensor price is only a minimum part of the system cost. As mentioned above, to have a PZT based SHM system, it is indeed necessary to equip the whole aircraft with a wiring system (including wires and connectors) and a specific compact power electronics hardware (including a control board, a smart processor on chip and analog to digital converters) needed to enable sensor control and allow signal acquisition. Considering the current market prizes, each sensor unit requires a dedicated local system whose cost is assumed as 230\$ per piezoelectric transducer when PZT-based actuation and sensing SHM system is considered. In addition, there is additional integration cost along with a possible concurrent cost for the system management. The former is due to the cost of the system installation. This slightly increases the aircraft manufacturing costs but it can be reasonably included within the overall costs for aircraft systems integration. Instead, the latter is due to the maintenance of the system itself and it is included within the maintenance costs of the aircraft.[11]

In addition to the direct cost of the equipment, it is worth noting that each component moved on board has its own weight, which has been also characterized according to the considered SHM solution. Sensors, wires, and connectors along with hardware needed for multi-channel actuation and acquisition lead to a weight penalty of about 80 g per transducer. That mass returns a sort of cost penalty which has been underestimated in many cost-benefit estimations so far, where a certain cost per flight hour induced by the added mass is considered without accounting any effect on aircraft performance.

Strictly related to prices is the spare cost, which could be defined as the sum of the cost of the engine and aircraft spare parts. Usually, the cost of aircraft spare parts is assumed as the 10% of the aircraft operational cost, while the engine spare part as the 30% of the engine cost. The Total Investment (TI) is the sum of the aircraft price and the spare costs.[11]

4. Unscheduled Maintenance

Scheduled maintenance involves routine checks and servicing at predetermined intervals, while unscheduled maintenance arises unexpectedly, often due to equipment failures or unforeseen issues. It can significantly impact operational costs and downtime, which is why understanding and managing these occurrences is vital. This section explores the application of the Poisson probability mass function (PMF) and cumulative distribution function (CDF) in predicting unscheduled maintenance events. By using these statistical tools, aviation operators can better estimate the frequency of failures and assess the associated costs. We will take a closer look at the A380 flights as an example to illustrate these concepts and their implications on maintenance strategies.

4.1 Predicting Unscheduled Maintenance Using Poisson Distribution

The Poisson probability mass function and cumulative distribution function are widely used in the aviation industry for modelling the occurrence of rare events, such as unscheduled maintenance incidents. The Poisson distribution is particularly suitable for estimating the number of events happening within a fixed period, given a known average rate of occurrence.

Let's consider an aircraft A S/N, which includes Engines, as an example to demonstrate the application of the Poisson distribution.

- Total number of A380 incidents: 10
- Mean Time Between Failures (MTBF): 355.75 hours
- Total Flight Hours (TFh): 3557.5 hours

Using these values, we can calculate the expected number of failures (λt) and the Poisson PMF and CDF to visualize the distribution of failures over time.

4.1.1 Calculation and Visualization

The Poisson distribution function $f(t)$ and cumulative distribution function $F(t)$ can be calculated using the following formula:

$$\lambda t = TFh / MTBF \dots \dots \dots (1)$$

By applying this formula and plotting the resulting Poisson PMF and CDF, we can generate a diagram that illustrates the probable number of A380 failures during the specified period.

The provided graphs (Figure-3) display both the probability distribution function (PMF) and the cumulative distribution function (CDF) for the predicted number of failures. The PMF shows the probability of a specific number of failures occurring, while the CDF represents the cumulative probability of up to a certain number of failures.

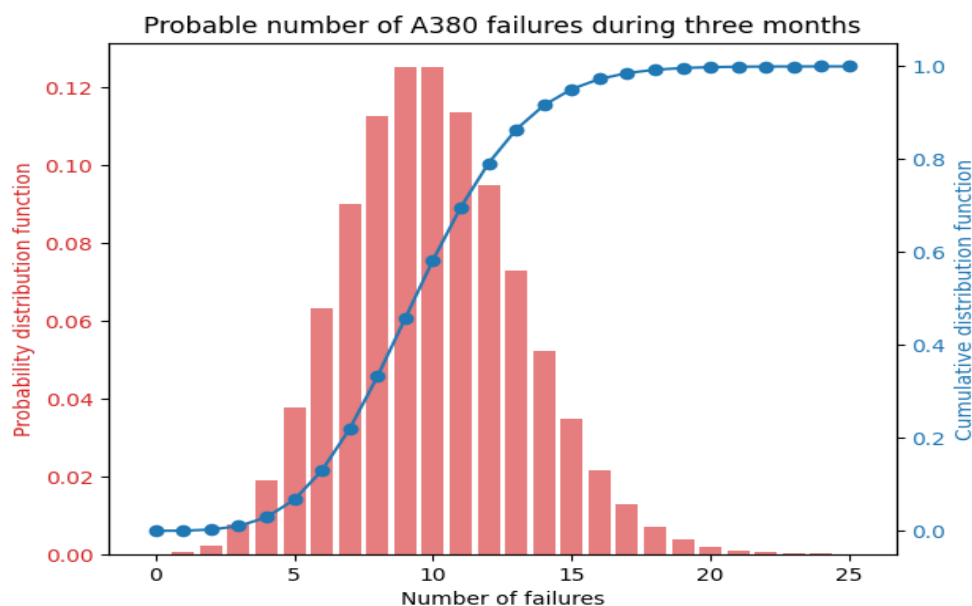


Figure 4- Probable number of A380 failures during three months

4.2 Cost Implications of Unscheduled Maintenance

In addition to predicting the occurrence of failures, it is essential to assess the cost implications of unscheduled maintenance. To determine the profitability of conducting extra checks beyond Mean Time

Between Failures (MTBF), several key metrics were considered: Mean Time to Repair (MTTR), Maintenance Down Time (MDT), part costs, repair costs per hour (including labor, facility, and VAT), incubation time of failures, and the cost of operational losses due to downtime. These metrics were derived from interview data, though simplifications and assumptions were necessary to adapt to our specific fleet size. A straightforward model was developed based on this data to assess the potential impact of extra checks on total costs. This model aims to predict the effectiveness of maintenance interventions by analysing the likelihood of detecting failures within their incubation time.

4.2.1 Exponential Distribution Model

The analysis employs an exponential distribution model to represent the probability of survival $R(t)$ and failure rate $F(t)$ within a defined period:

$$R(t) = e^{-\lambda t} \dots\dots\dots(2)$$

$$F(t) = 1 - e^{-\lambda t} \dots\dots\dots(3)$$

Here,

$$\lambda = \frac{1}{MTBF} \dots\dots\dots(4)$$

This model helps estimate the probability of revealing failures during specific time intervals, providing insights into the optimal timing for conducting preventive checks. By understanding when failures are most likely to occur and be detected, maintenance strategies can be optimized to minimize operational disruptions and costs. The Figure 2 shows the exponential distribution of the with which we have found the optimal percentage of failures across time.

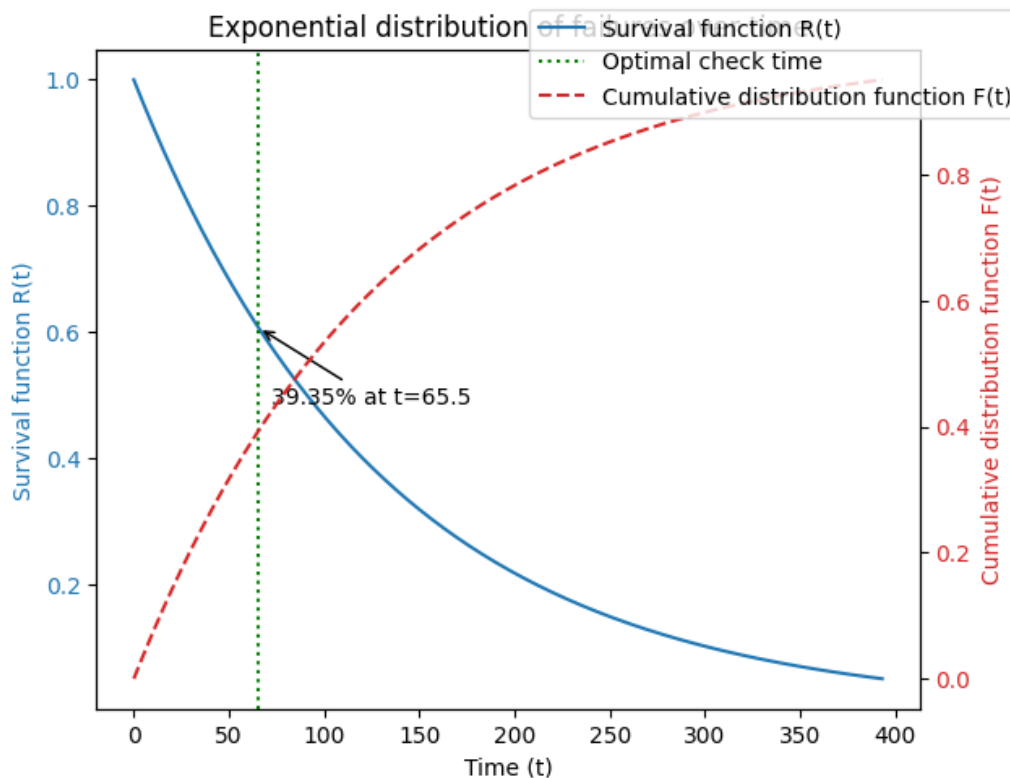


Figure 5- Exponential distribution of failures over time

Thus, we can compute the approximate savings, or losses, that an additional check would result in if we know the total flight hours within the time frame TFh, the cost of the unscheduled maintenance (i.e., down time DT_{cost} , incubation time t_i , MTBF), the length of time an additional check would take C_t , the interval of additional checks C_i , MTTR (to repair the failure), MDT, the maintenance cost per hour M_{cost} , and the cost of the part required R_{cost} .

1. Number of Expected Failures (N_f):

$$N_f = \frac{TFh}{MTBF} \dots\dots\dots(5)$$

2. Total Cost if No Extra Checks ($Tot_c_no_checks$):

$$Tot.c_{no\ checks} = (MTTR * M_{cost} + P_{cost} + MDT * DT_{cost}) * N_f \dots\dots\dots(6)$$

3. Total Cost of Extra Checks (Tot_c_checks):

$$Tot.c_{checks} = C_t * M_{cost} * \frac{TFh}{C_i} \dots\dots\dots(7)$$

4. Total Cost to Repair Failures Revealed by Extra Checks ($Tot_c_revealed_f$):

$$Tot.c_{revealed.f} = (MTTR * M_{cost} + P_{cost}) * F_{revealed} \dots\dots\dots(8)$$

5. Total Cost for Unrevealed Failures ($Tot_c_unrevealed_f$):

$$Tot.c_{unrevealed.f} = (MTTR * M_{cost} + P_{cost} + MDT * DT_{cost}) * (N_f - F_{revealed}) \dots\dots(9)$$

6. Final Result (Savings/Losses):

$$result = Tot.c_{no\ checks} - (Tot.c_{checks} + Tot.c_{revealed.f} + Tot.c_{unrevealed.f}) \dots\dots(10)$$

All of the aforementioned figures' approximations were assessed while taking A380 into account. The values provided are estimates because airline data is private. These calculations provide a comprehensive view of the potential savings or losses resulting from different maintenance strategies. By applying the Poisson distribution to predict unscheduled maintenance events and evaluating the associated costs, aviation operators can make informed decisions to optimize maintenance strategies. Understanding the trade-offs between performing extra checks and managing unscheduled failures helps in reducing operational costs and enhancing aircraft reliability.

Table 4- Cost-Benefit Analysis of Predictive Maintenance Based on Poisson Distribution

	Description	Values
1	Total flight hours (TFh)	3557.50
2	Incubation time (t_i)	65.50
3	MTBF	355.75
4	Interval of extra checks (C_i)	200.00

5	Cost of extra checks (Ct)	2.00
6	Mean time to repair (MTTR)	10.00
7	Maintenance down time (MDT)	10.00
8	Repair cost (Rcost)	\$8000.00
9	Maintenance cost (Mcost)	\$177,875.00
10	Downtime cost (Dtcost)	\$10000.00
11	Number of expected failures (Nf)	10.00
12	Failures probable revealed (F_revealed)	3.90
13	Total cost if no extra checks (Tot_c_no_checks)	\$18,867,500.00
14	Total cost of extra checks (Tot_c_checks)	\$6,327,903.13
15	Total cost to repair failures revealed (Tot_c_revealed_f)	\$6,968,325.00
16	Total cost for the rest of the failures not revealed (Tot_c_unrevealed_f)	\$11,509,175.00
17	Result (savings/losses)	\$5,937,903.12

4.3 Future Scope

Maintenance managers and engineers frequently use the data they collect in their daily operations, yet this information is often not shared with other organizations. Maintenance data from different sites worldwide remain underutilized. Effectively sharing relevant information among connected users in a uniform and accurate manner, and providing it timely, can significantly enhance its statistical impact and provide competitive advantages. Real-time monitoring algorithms can be incorporated using fibre optic and piezoelectric sensors, which when combined with mathematical models can enhance these predictions. Furthermore, all maintenance agencies in the world can access a digital version of the aircraft thus improving preparedness and reducing down-time. The stocking and purchasing process could be optimized by looking at maintenance records. It is therefore possible to measure maintenance system performance and compare environmental impacts regarding repair operations by sharing information on technical systems and location of shared asset. Future work includes conducting a comprehensive cost-benefit analysis of these integrated approaches.

According to Figure 6, the fibre optic sensor network in the flight sends data to the Data Acquisition System, where the data is stored for training and testing. This data is then sent to the Real Time Processing Unit, a subsystem of the Central Processing Unit (CPU). The CPU houses the Machine Learning (ML) model, which performs predictive real-time maintenance. The processed data is stored in the Flight Management System and displayed on the cockpit's dashboard alert system for real-time monitoring and alerts.

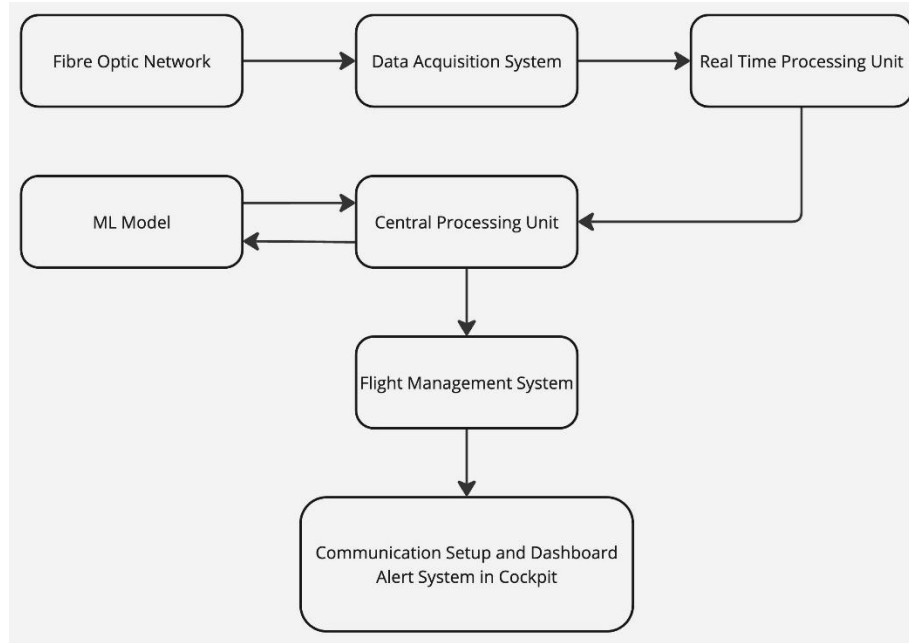


Figure 6- Real Time Predictive modelling using Fiber Optic Network

5. Conclusion

The Structural Health Monitoring (SHM) systems incorporation in the aircraft maintenance specifically for Airbus A380, is a big step towards enhancing safety, reducing costs and improving efficiency of maintenance. The importance of predictive maintenance is well demonstrated by the detailed case studies that highlight the benefits of SHMs such as real-time data provision and early detection of structural problems to avoid costly disaster. Our findings indicate that initial investment in SHM systems may be high but over time, savings made significantly outweigh this cost as well as leading to operational advantages. In this regard, implementing SHMs can have significant effect on unscheduled maintenance, downtime costs and repair expenses for improved safety with optimal use of resources. Technologically speaking, piezoelectric and fibre optic sensors used in SHMs offer robust real-time monitoring solutions. Each type of sensor has its own strengths making it possible to design customized ones according to different demands. All in all, there is no way around it; aviation industry must adopt SHMs to realize increased safety levels while maintaining high efficiency at reduced costs. Subsequent studies are necessary to refine SHM technologies and include them within other tools like predictive maintenance before implementation procedures become standardized.

Contact Author Email Address

Mail to: vageeshasm.ae20@rvce.edu.in or vageeshasharma13@gmail.com

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