DOI: 10.13009/EUCASS2019-198

# Inspection schedule adjustments through Monte Carlo Analysis

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## Abstract

Once that an Aircraft family enters into service, a continuous monitoring of the fleet is performed to ensure its Airworthiness. Occasionally, this continuous monitoring reveals that certain equipment installed in the aircraft have failure modes governed by wear-out process, in which the failure rate increases with time. When these kinds of malfunctions are discovered, sometimes is necessary to impose periodic inspections until the defect is removed. The objective of this study is to show the benefits of using the Monte Carlo analysis to adjust the inspection schedule, keeping aircraft safety levels whilst the impact over the operators is minimized.

## 1. Introduction

The International Civil Aviation Organization (ICAO), through the Airworthiness Manual [1], defines the Continuing Airworthiness as "The set of processes by which an aircraft, engine, propeller or part complies with the applicable airworthiness requirements and remains in a condition for safe operation throughout its operating life".

Based on the recommendations captured in the ICAO Airworthiness Manual [1], European Regulations provide, through the Implementing Rules [2] and the Interpretative Material [3], specific requirements to the Type Certificate Holder:

- Put in place a system for collecting, investigating and analyzing reports and information related to occurrences which cause or might cause adverse effects on the continuing airworthiness of the product.
- Inform about the implemented system to all known operators
- Report to the Airworthiness Authorities (AA) any failure, malfunction, defect or other occurrence of which it is aware related to a product and which has resulted in or may result in an unsafe condition (not later than 72 hours after the identification of the possible unsafe condition).
- Investigate the reason for the deficiency and report to the AA the result of its investigation and any action it is taking or proposes to take to correct the deficiency.
- Submit the relevant data to the AA in case that the Agency finds that an action is required to correct the deficiency.

When evidence shows that the safety level of an Aircraft may be compromised (an unsafe condition has been determined to exist in an aircraft), the AA may issue an Airworthiness Directive (AD). This AD is a regulatory document which identified aeronautical products in which an unsafe condition exists, and where the conditions is likely to exits or develop in other aeronautical products of the same type design. It prescribes mandatory corrective actions to be taken or the condition or limitations under which aeronautical products may continue to be operated [1].

In case of the corrective actions imposed by the AD is an periodic inspection, depending on the complexity of the problem and the information available at the time of the AD release, the periodicity of the inspections can be initially imposed based on engineering judgement, being necessary to perform a dedicated analysis to adjust the schedule of the inspections to minimize the impact over the operator, without impacting the safety levels.

Main purpose of this report is to present, through a real case observed in an in-service Aircraft fleet, the benefit of using the Monte Carlo Analysis to adjust the inspection schedule and thus minimizing the impact over the operators without compromising the safe operation of the Aircraft fleet.

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## 2. Declared engine in service occurrence

Several In-service occurrences, related with the degradation of the same internal element of a particular set of engines, made necessary to perform a detailed investigation about the source of the event and its potential mitigation.

Root cause analyses, carried out to understand the nature of the failure, pointed out to an accelerated wear out process of an engine component, due to unexpected high vibrations exposure. Analysis revealed that the deterioration sequence of the component consisted of:

- Initial crack on the item edge
- Local crack propagation in radial direction close to the edge
- Liberation of small fragments at several locations around the affected edge
- Further crack propagation in axial direction
- Dislocation of the forward part of the component from its attachment point

Particularly, as the affected item was not an engine critical part, investigation demonstrated that, either the liberated small pieces or the complete dislocated part of the item would not originate an immediate engine in-flight shut down, being necessary the occurrence of other random events, like the displacement of the detached part to a more sensible area.

Additionally, due to the particular location of the affected item, its progressive degradation could not be identified directly by the flight or ground crews as this event does not lead directly to any system malfunction or the triggering of any dedicated warning in the cockpit, being necessary to perform a specific boroscopic inspection to detect it.

## 3. Failure mode analysis and risk evaluation

The most frequent methodology used in the aviation industry to assess the reliability of the failed airplane systems or components is the two parameter Weibull analysis [4]. The main reasons for its wide spread use are [5]:

- Quantifies reliability (or risk of failure) as a function of the age of the product.
  - Infantile failure: Reliability improves with age / Decreasing hazard rate
  - Random failure: Reliability constant with age / Constant hazard rate
  - Wear-out failure: Reliability decreases with age / Increasing hazard rate
- Provides reasonably accurate failure analysis and failure forecasts with extremely small samples
- Provides a simple and useful graphical plot of the failure data
- May consider the effect of non failed units

This Weibull distribution has two parameters, the Characteristic Life ($\eta$) and the Slope ($\beta$). The Characteristic Life is the location parameter, and represents the age at which 63,2% of the units will fail. The Slope is called the Shape parameter and determines which member of the Weibull family of distributions is most appropriate (Figure 1):

- Infantile failure: $\beta < 1$
- Random failure: $\beta \approx 1$
- Wear-out failure: $\beta > 1$

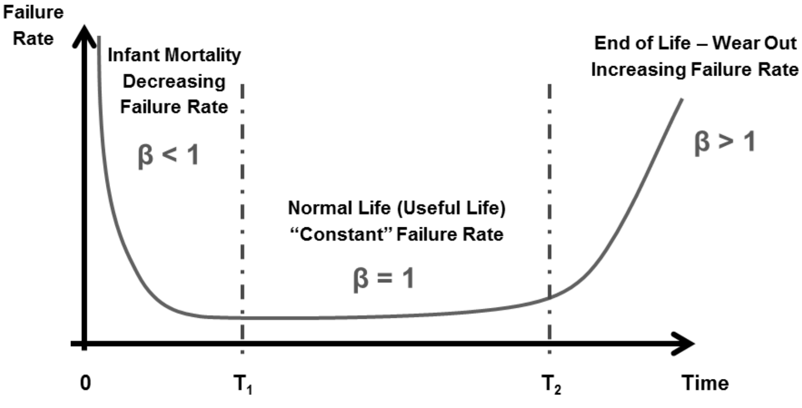

Figure 1: Relationship between beta and failures throughout the life of a component

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Data recorded during the investigations of the in-service occurrence were used as the input data for the two parameter Weibull statistical analysis. To perform this analysis, all the items affected by the detected defect were considered, avoiding considering components known to be free of risk, as this consideration may increase artificially the value of the Characteristic Life, being the results more optimistic.

Results of the Weibull analysis of the data recorded during the investigation revealed that the defect was in line with a wear-out failure mode, and therefore its failure rate increases with time. The fact that the failure rate increases with time made necessary to perform a dedicated analysis to assess new safety risk levels as a function of the time, in order to evaluate if Part 21 requirements [3] were accomplished in terms of declaration of unsafe conditions and time to implement a corrective action.

An unsafe conditions exists if "there is factual evidence that an event may occur that would result in fatalities, usually with the loss of the aircraft, or reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions […] unless it is show that the probability of such an event is within the limit defined by the applicable certification specifications" [3].

Therefore, taking into account statistical results obtained through the two parameter Weibull analysis, it was declared that the defect represented an unsafe condition as, due to the wear out nature of the phenomena, and the subsequent increase in the failure rate with the time, the probability per flight hour overcome the safety objectives imposed by the certification specification before the end of the life of the Aircraft, being necessary to impose a corrective action in a short period of time to avoid overcoming such safety objectives limit. Additionally, based on the initial uncertainties of the root cause of the failure, and its potential repercussion, an Airworthiness Directive (AD) mandating a periodic boroscopic inspection of the affected area of the engine was issued by the Airworthiness Authorities with a very tight inspection threshold to ensure preventive detection of the crack initiation and propagation.

Initial inspection threshold was based on engineering judgement, with the purpose of accelerating the release of the AD and thus preventing the occurrence on any feared event in the in-service fleet (In Flight Shut Down [IFSD] due to early degradation of the affected item). Once that the mandatory inspections were performed and the risk mitigated, and taking into account the operational impact of the inspections schedule, it appeared necessary to perform a numerical analysis to demonstrate the effectivity, and adjust, if possible, the interval between consecutive inspections.

Due to the nature of the failure (wear out process with increasing failure rate) traditional risk levels evaluation using fault trees analysis was not applicable (only valid for failure modes with constant failure rate), being necessary to use alternative methods to perform this study.

## 4. Monte Carlo analysis

Monte Carlo simulation is a versatile technique that allows obtaining numerical solution to problems which are too complicated to solve analytically [4]. This versatility allows using this kind of model for a wide range of problems involving areas as diverse as physics, astronomy, engineering, biology, artificial intelligence, telecoms, finance, business and reliability problems among others, being the common factor between all these problems the probabilistic nature of their inputs.

This method is based on the massive repetition of the same experiment, where a specific value for each input parameter is randomly selected in each iteration from the associated probability function for that parameter. In this way, by using probability distributions, variables will have different input values, leading to a probabilistic outcome that will tend to the expected value, in accordance with the law of large numbers.

Analyzing a problem through a Monte Carlo simulation involves the following steps [4]:

- Define the problem to be analyzed
- Identify the parameters that contribute to or influence the problem
- Define a mathematical expression for each probabilistic input parameter
- Develop a flow chart to describe the relationship between the output event (problem) and the input parameters
- Define the content and format of the output desired from the simulation
- Develop a computer program which corresponds to the system flowchart and which summarizes results in the desired format.
- Operate the computer program all the times necessary to obtain the desired confidence in the simulation results

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Among other uses in the Aeronautical area, safety assessment guidelines for transport airplanes [4] explains the benefit of using this kind of analysis to check the effectivity of the corrective actions and inspections threshold after defect detection, being possible to judge the benefit of various schedule inspections. Additionally, Reduction of Fuel Tank Flammability in Transport Category Airplanes CFR [6] proposes a Monte Carlo model for calculating fuel tank flammability, which determines the fuel tank flammability exposure for numerous simulated airplane flights during which various parameters are randomly selected, being the results of these simulations averaged to determine the fleet average fuel tank flammability exposure.

In line with these guidelines, a Monte Carlo model was generated to evaluate the effect of the corrective actions and the possibility of improve them. This model is focused on the analysis of the engine life, evaluating if the defect will be detected during each of the mandatory inspection (allowing a safely replacement of the engine), or, on the other hand, if the interval between the inspections is too high as to allow the combination of several unexpected engine failures during the same flight, leading to a potential unsafe condition. Final outcome of the model will be the probability of IFSD occurrences per flight hour, grouped per flight phase, just to compare the results with the corresponding values of associated failure conditions identified in the Engine System Safety Assessment (SSA).

## 5. Monte Carlo Model

### 5.1 Random Inputs

To perform the analysis, a Monte Carlo model was developed considering the following random inputs:

- Crack initiation: Time at which a detectable crack appears in the affected item. This time is randomly selected from a Weibull Distribution, based on the data gathered during the inspections over the fleet.
- Engine failure due to the release of the portions of affected item: Time at which the engine fails (shut down) due to the consequence of the release of any piece of material of the worn out item. This time is the combination of the:
    - crack initiation time
    - crack propagation time until the detachment of portions of material
    - time between the detachment of the fragment and the engine failure

  Instead of evaluating this time as the sum of three random variables, it is randomly selected from a Weibull Distribution. A conservative approach was taken, considering that all the engines inspected and found with released portion of material would fail in the following hour.
- Engine Failure due to non-inherent causes: Time at which the engine fails due to a cause non-related with the event under study. This value is randomly selected from an exponential distribution, based on the IFSD failure rate extracted from the Engine SSA.
- Length of the mission: Flight time is randomly selected from a Log Normal distribution based on estimation of A/C flight distributions. Cruise time will depend of the flight time, fixing the time duration for the other phases in accordance with original Engine SSA hypothesis.
- Inspection schedule: It shall be highlighted that the Inspection schedule is a parameter that shall be fixed at the beginning of the model, and therefore it is not a random variable for each particular analysis but an additional parameter to be considered for the analysis.

### 5.2 Monte Carlo Model

Based on these random parameters, proposed Monte Carlo model to analyze the benefit of the mandatory inspection and its potential adjustment is summarized in the following steps:

A. Initial Setup Of the Monte Carlo input parameters
    1. Randomly sample the life of each of the affected engines installed in one A/C at which the following event occurs:
        a) Crack initiation in the affected item
        b) Engine failure due to the release of portions of affected item
        c) Engine failure due to non-inherent causes
    2. Randomly sample the length of the missions along the A/C life
        a) Evaluate the duration of the flight phases based on the mission length for each flight.
    3. Fix the Inspection Schedule at which each engine will be inspected
        a) Initial inspection since new engine installation
        b) Further recursive inspections

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B. Perform an individual flight
  4. Check at the end of each flight:
    a) Number of events (IFSD) occurred
    b) If any inspections shall be triggered as per defined inspection schedule
  5. Perform Engine replacement for those engines failed or inspected with some findings:
    a) Randomly sample the life of each new engine installed in the A/C as per Step 1
    b) Fix the time at which each replaced engine will be inspected (initial and recursively) as per Step 3
  6. Record the number of events and group then based on their repercussion (Number of engines failed during the flight and flight phase)

C. Repeat the individual flight to accumulate enough number of Flight Hours
  7. Repeat Steps 4 to 6 until achieve the end of the A/C life
  8. Repeat Steps 1 to 7 for each one of the A/C fleet
  9. Repeat Steps 1 to 8 to accumulate the sufficient number of Flight Hours (FH) as to achieve a good confidence level of the results (~$10^{11}$ FH)
  10. Evaluate global IFSD rates based on total number of events and total number of FH

## 6. Model validation

To check the accuracy of the Monte Carlo model, a model validation was performed by means of comparing the results obtained through the model with the probabilities associated to the following failure conditions, captured in the System Safety Assessment (SSA):

- Loss of thrust in 3 engines in all flight phases
- Loss of thrust in 2 engines during Take-Off
- Loss of thrust in 2 engines during climb, approach and landing
- Loss of thrust in 2 engines during Cruise / Descent
- Loss of thrust in 1 engine during Take-Off
- Loss of thrust in 1 engine in all flight phases

To perform this analysis, and with the purpose of analyzing similar configurations, the following minor modifications were implemented within the Monte Carlo model:

- All the engines life were evaluated based on the SSA random failure probability (no engine failure due to crack initiation and propagation were considered)
- Boroscopic inspections related with AD were not considered

To capture events considered as extremely remote ($P < 10^{-7}$ / FH) and extremely improbable ($P < 10^{-9}$ / FH) within the SSA, Monte Carlo model was executed enough number of iterations as to accumulate around $10^{11}$ Flight Hours. Results obtained after running the model such number of iterations have been compiled in Table 1. These values confirmed that, in general, the results obtained through the Monte Carlo analysis matched the probability values compiled in the Engine SSA, being the biggest difference identified for the failure condition related to the “Loss of thrust in 2 engines during Take-Off”. This under estimation will be taken into account during the analysis of the final results.

Table 1: Comparison between Engine SSA Failure Conditions probabilities and Monte Carlo Analysis Results

| | **Classification** | **Engine SSA** | **Monte Carlo** |
|---|---|---|---|
| Loss of thrust in 3 engines in all flight phases | Catastrophic | $2{,}7 \times 10^{-12}$ | $< 4{,}6 \times 10^{-11}$ |
| Loss of thrust in 2 engines during Take-Off | Catastrophic | $4{,}3 \times 10^{-10}$ | $4{,}6 \times 10^{-11}$ |
| Loss of thrust in 2 engines during climb, approach and landing | Hazardous | $8{,}3 \times 10^{-10}$ | $5{,}5 \times 10^{-10}$ |
| Loss of thrust in 2 engines during Cruise / Descent | Major | $5{,}8 \times 10^{-9}$ | $3{,}8 \times 10^{-9}$ |
| Loss of thrust in 1 engine during Take-Off | Major | $1{,}9 \times 10^{-6}$ | $8{,}8 \times 10^{-7}$ |
| Loss of thrust in 1 engine in all flight phases | Minor | $1{,}7 \times 10^{-4}$ | $9{,}6 \times 10^{-5}$ |

## 7. Studies and results

Once the model was validated, two different studies were carried out:

- Assessment of the mandatory inspection effectiveness
- Adjustment of the inspection threshold

In all the cases, to be able to capture events considered as extremely remote ($P < 10^{-7}$ / FH) and extremely improbable ($P < 10^{-9}$ / FH), Monte Carlo model has been executed enough number of iterations allowing the accumulation of around $\sim 10^{11}$ Flight Hours.

### 7.1 Assessment of the mandatory inspection benefit

Main purpose of this first study was to evaluate the impact on the probability of occurrence per flight hour of the most critical failure conditions declared within the Engine SSA, when the mandatory inspections are performed on the engine. Similar to the validation cases, failure conditions analyzed were:

- Loss of thrust in 3 engines in all flight phases
- Loss of thrust in 2 engines during Take-Off
- Loss of thrust in 2 engines during climb, approach and landing
- Loss of thrust in 2 engines during Cruise / Descent
- Loss of thrust in 1 engine during Take-Off
- Loss of thrust in 1 engine in all flight phases

Figure 1 shows the result of the evaluation, in which it can observed that, due to the presence of an unexpected wear out process in the A/C fleet ("Without AD" data), the probability of failure per flight hours increases in comparison with those declared in the Engine SSA ("SSA" data), overcoming in some case the safety objectives (horizontal thickest lines), but, thanks to the imposition of the mandatory inspection, an acceptable risk level is recovered ("AD" data). This analysis demonstrates that the inspection threshold imposed initially, based on engineering judgment, allows restoring the initial safety level and therefore ensures the accomplishment of the airworthiness requirements.

It shall be noted that, for the failure condition "Loss of thrust in 2 engines during Take-Off", in which the Monte Carlo model under estimate the SSA probabilities, recovers the initial "SSA" values once that the application of the AD is taken into account, and therefore it is considered that there is no risk associated to a potential underestimation of this failure condition.

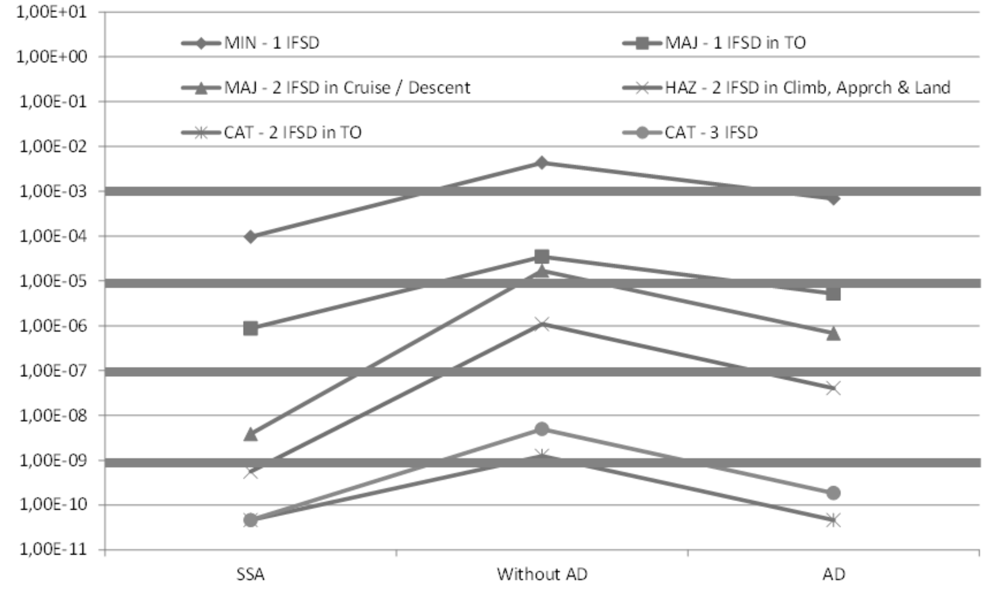

Figure 1: Risk level comparison

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### 7.2 Adjustment of the inspection threshold

Once that it has been demonstrated that initial inspection threshold based on engineering judgement allows recovering the original risk levels, the second study consists in the performance of a sensitivity analysis to calculate the maximum interval between two consecutive inspections that keeps the risk within acceptable level.

For such purpose, initial Monte Carlo simulation was repeated, but considering an inspection threshold 2.5, 5 and 10 times higher than the original one to check the risk level evolution.

Figure 2 shows the results of the second analysis, in which it can be observed how the risk level increases in the same way as the inspection threshold is increased. For inspection thresholds 2.5 and 5 times higher than the original one, the risk level are still within safety objectives, not being the case for an inspection threshold 10 times higher, as the probability of failure per flight hour for three of the five failure conditions analyzed overcome the safety limits.

This second analysis demonstrates that, although the risk levels are recovered with the inspection threshold imposed initially (based on engineering judgement), it was too restrictive, forcing to the operators to perform more inspections than the ones really needed to cover the airworthiness safety requirements. Therefore, this study set up the basis for the review of the inspections threshold in order to adjust it to the reality at the same time that the safety objectives are met.

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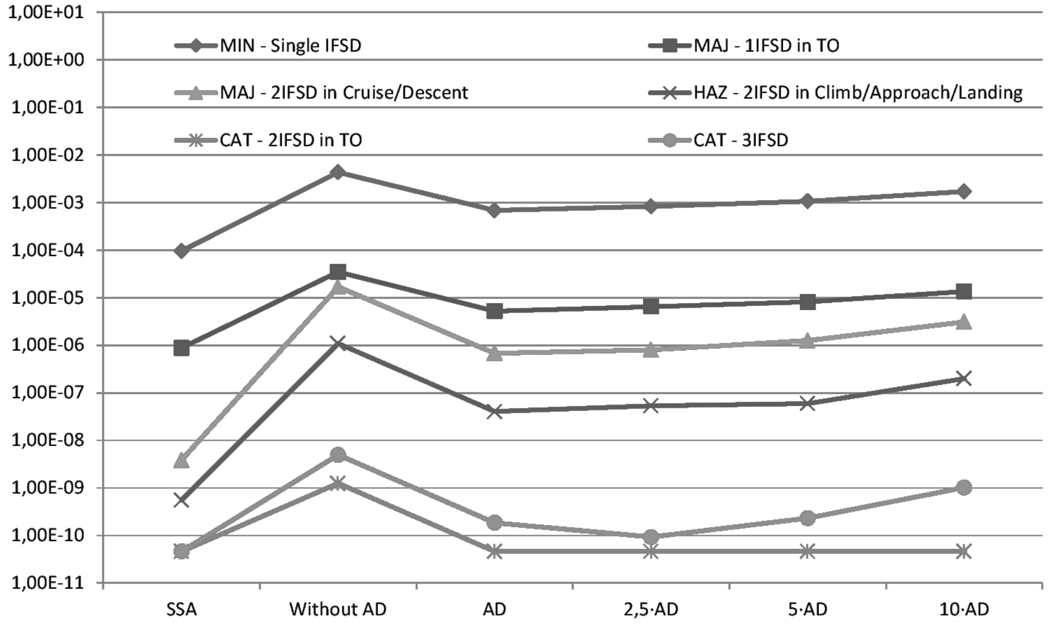

Figure 2: Risk level evolution as a function of the inspection threshold

## 8. Conclusions

This study presents the Monte Carlo Method as an alternative to evaluate the benefit of the mandatory inspections for those events which are affected by failure modes with an increasing failure rate with time (wear-out processes).

A specific model has been developed to analyze the mitigation effect over the global risk levels of the mandatory inspections imposed after the detection of the in-service events related to the accelerated damage of a non-critical part of the engines.

Results presented along this study, based on the application of a dedicated Monte Carlo model, reveal that, firstly, the inspection threshold imposed initially (based on engineering judgement), allow restoring the initial safety level, and secondly, that the initial interval between two consecutive inspections was too conservative, being possible to

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multiply it by 5 without impacting the accomplishment of the safety requirements, alleviating in this way the operators constraints associated to the unnecessary repetition of inspections.

Therefore, considering the Monte Carlo analysis as a recommended practice for this kind of studies, the output of this analysis allowed setting up the basis for the review and optimization of the mandatory inspection threshold imposed by the Airworthiness Authorities.

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