

SYSTEM ANALYSIS OF PROGNOSTICS AND HEALTH MANAGEMENT SYSTEMS FOR FUTURE TRANSPORT AIRCRAFT

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Abstract

This paper provides a lifecycle analysis of the use of prognostic systems in future or present aircraft. By simulating aircraft operation and maintenance and modeling resulting costs and revenues it gives a profound economic assessment of a technology implementation. The proposed method uses component specific failure distribution functions derived from in-service data to model component failure behavior and includes performance levels of prognostic systems to account for imperfect sensor systems or prognostic algorithms.

The study demonstrates that Prognostics and Health Management (PHM) systems for a selected aircraft system can enable a significant reduction of unscheduled events, leading to additional aircraft utilization and an increase in net present value (NPV) of up to 0.48 % in case of a perfect PHM system. It is shown that many factors influence whether the implementation of PHM for a specific system may be beneficial in the end.

1 Introduction

Competition in passenger and freight air transportation has increased steadily in recent years. While air travel has grown significantly at the same time, the profit margins of airlines are very poor. A net operating profit margin of

1.4 % is expected for 2012, while the system-wide mean value of global commercial airlines since 2003 is 1.9 % [1].

The aircraft operators are under great pressure to increase aircraft availability and operability in the future and continue to reduce the cost of aircraft operation. Reductions of maintenance downtimes and the prevention of operational interruptions can help to achieve these objectives.

Technical and aircraft equipment was the most occurring direct delay category in 2006, with 10.2 % of total delays [2]. When aiming for significantly higher reliabilities of future aircraft, it should be considered that 20 % to 50 % of all unscheduled removals are no-fault-found¹ (NFF) [3].

PHM systems may help to reduce operational interruptions due to unscheduled maintenance events, and maintenance downtimes due to (unnecessary) preventive maintenance. While significant advances in PHM systems are announced by industrial and academic research, several challenges have to be resolved for the onboard deployment of an aircraft-wide system [5]. Besides the solving of technical issues one important prerequisite of an implementation is the provision of a reliable cost-benefit assessment of the onboard use of PHM. Such an analysis must be able to capture

¹ An item removal is classified as NFF when no fault is exhibited during subsequent acceptance test [4].

all relevant impacts of the technology on aircraft operation and maintenance over the aircraft lifecycle.

1.1 Impacts of Prognostic Systems

Prognostic concepts can positively influence the areas safety, maintainability, logistics, lifecycle costs, system design and analysis, and reliability of a product [6]. It has to be differentiated between general impacts, which can be also achieved through an installation of PHM in existing aircraft, and the implementation in future aircraft during an early design stage.

1.1.1 General Impacts of PHM

Prognostic systems provide advanced warnings of failures with estimates of the remaining useful life (RUL) of an item. RUL estimates are calculated by prognostic algorithms based on individual states of health and (estimated) future degeneration processes. A successful failure prognosis enables a repair or replacement of the degraded item before the critical failure occurs [7].

In addition no-fault-found (NFFs) can be reduced based on the health monitoring capability of PHM, which localizes failure root-causes. The mentioned effects can lead to significant reductions in maintenance downtime and costs [8]. Furthermore the prevention of NFFs reduces the number of events in the component shops and related logistics costs.

The benefits and drawbacks, which can be achieved in a specific application, depend on the operational constraints, the current maintenance concept, and the influence of the monitored item on the safety and operational reliability of the aircraft. Furthermore it has to be considered that the development and acquisition of PHM systems can be very costly. It should always be evaluated whether an implementation of PHM or an increase in reliability of the corresponding system or component is the most beneficial solution. Therefore it has to be analyzed very carefully whether the implementation of PHM for a specific system or component would be cost-efficient.

Most existing approaches for a PHM development are aimed at its implementation in existing aircraft [6]. This allows primarily an improvement of operational reliability by reducing delays and cancellations caused by unscheduled maintenance events and NFFs.

The use of PHM for items subject to a preventive (i.e. time-based) maintenance strategy leads to a shift towards a predictive (i.e. condition-based) maintenance strategy. The major benefits in this case are reductions of waste of (component-) lives and of overall maintenance efforts. These effects additionally influence spare parts pooling due to reduced spare parts demand and thereby allows a reduction in capital commitment.

1.1.2 Impacts of PHM in Future Aircraft

In the long-term the integration of prognostics in future aircraft during early design stages seems more promising. Besides the expected better system-wide performance in integrated solutions, additional benefits can arise. PHM technologies installed in future aircraft could help to reduce scheduled and unscheduled maintenance and consequently increase the aircraft availability and operability. Significant shares of today's scheduled maintenance tasks are related to inspections, which may become obsolete in future aircraft when equipped with PHM systems. Many safety critical items are subject to a time-based maintenance today. If a PHM system can ensure a reliable detection of an imminent fault of this item, its useful lifetime can extend substantially by applying a condition-based maintenance.

Highly reliable prognostic systems may allow reductions of safety margins and redundancies in several aircraft systems while guaranteeing the same or even higher safety standards. This would enable significant reductions in aircraft weight and production costs.

The use of prognostics also has consequences for maintenance planning and scheduling. Adapted maintenance concepts are required, when maximal benefits of PHM should be realized. Today's maintenance programs are characterized by preventive and reactive tasks. While preventive tasks with fixed

intervals are foreseeable and easy to plan, time and effort for reactive work is more difficult to plan as they arise from the results of inspections or fault reports. A wider use of prognostics lowers the portion of preventive time-based tasks and thereby reduces the predictability of future maintenance work. In contrast to today's maintenance concepts with mainly predetermined and preplanned activities, more flexible maintenance planning processes are needed to support prognostics in an optimal way. Maintenance activities have to be grouped together and performed at the right point of time depending on estimated RUL [9]. The goal is to find the optimum from short aircraft downtimes and low maintenance costs while considering constraints like aircraft rotation planning and limited maintenance capacities.

1.2 Technology Evaluation of Prognostic Systems

The implementation of PHM is one technology among many others to reduce unscheduled maintenance events and NFFs. Economic assessments of PHM applications for aircraft have been discussed by other studies [10-13]. Most studies propose cost analysis or cost-benefit analysis for a specific application. Typical measures are lifecycle costs (LCC) or return-on-investment (ROI) estimates of the implementation costs and the potentials for cost avoidance. Some approaches calculate the net present value (NPV) of a PHM use. Most studies do not consider uncertainties of critical inputs [11; 13]. Feldman et al. [13] propose a detailed methodology for determining the ROI of PHM including a stochastic discrete event simulation to model maintenance costs of a single line replaceable unit (LRU). Though considering uncertainties of inputs, the study does not incorporate the interdependence between maintenance and flight operation. Instead fixed cost rates for unscheduled aircraft downtimes are used to calculate the potential cost avoidance through PHM. No approach for an assessment of PHM could be identified in literature that is able to conduct a complete lifecycle simulation including both, a modeling

of the flight operation and of the maintenance events.

One major benefit of PHM – an increase of aircraft utilization through the reduction of delays and cancellations – cannot directly be assessed by existing methods.

In a real world application, any PHM system can show malfunctions. There are two types of PHM failures. A false alarm is given, when a prognostic algorithm announces an impending failure of an item though it is in good condition. When a PHM system does not report an impending failure of a monitored item in sufficient time, a missed failure is given.

Therefore, uncertainties and prognostic performance levels including probabilities of false prognoses and missed failures have to be considered [5].

Usually, mean lifetimes or mean times between failures are used to describe the failure behavior of technical items. In reality, random effects through (unknown) individual loads and production tolerances can lead to large variances in failure behavior. Therefore, the use of mean lifetimes reflects an incomplete picture and is not sufficient when the actual time of a failure event in aircraft lifecycle is relevant.

1.3 Goal of Study

The goal of this study is to propose an appropriate method for analyzing the economic potentials of a PHM implementation in aircraft. The applied methodology should be generic and feasible to analyze existing and future aircraft. The focus of this paper is on an existing 150-seat short-range aircraft with broad operational experience, i.e. long-term benefits of PHM are not included in the following analysis. The goal is to identify the economically most promising systems for a prognostics use. A detailed examination of the technical feasibility is not part of the presented analysis.

As stated in chapter 1.2, an approach is needed, that considers all phases in aircraft lifecycle and includes all relevant impacts of PHM systems and existing interdependencies with other elements of the air transportation system in a comprehensive way. In particular the selected approach has to consider the

influence of a PHM use on aircraft operation. The use of a discounted cash-flow method is required to take into account the time value of money when assessing an aircraft over its entire lifecycle.

To consider uncertainties in component failure behavior, the methodology used in the study should be based on individual component failure distribution functions. Performance levels (i.e. false alarm rates and missed failure rates) of PHM systems have to be included to account for imperfect sensors or prognostic algorithms.

2 System Analysis Approach

The following chapter provides an overview of the developed lifecycle approach, the analysis of component failure behavior, and the aircraft operations and maintenance simulation.

2.1 Lifecycle Approach

The three major commercial stakeholders in the air transportation system – aircraft manufacturer, airlines and MROs – have conflictive goals, since all striving for profit maximization. New technologies for the air transportation system must therefore not only lead to technical improvements, but have to show economic advantages compared to the current system.

Direct operating cost (DOC) is an established metric to perform economic valuation of existing aircraft or future aircraft concepts [14; 15]. Standard DOC methods account for crew expenses, landing and navigation charges, maintenance cost, fuel cost, depreciation, insurance cost, and interest. DOC formulae use global technical, operational, and economic parameters to come up with an average DOC value on a flight-cycle or flight-hour basis.

When assessing technologies and processes with impacts on the air transportation system level, all phases of the life cycle and interdependencies with other system elements have to be considered. New maintenance concepts influence maintenance cost and aircraft

availability. To capture time and cost aspects, a lifecycle cost-benefit analysis has to be conducted.

The NPV is a common metric to quantify a project's net-contribution to wealth for a certain period of time, while accounting for the time value of money and the opportunity cost of capital [16]. It can be calculated as given in Eq. (1), where C_0 is the initial investment (i.e. aircraft price) and C_i is the cash-flow in the i -th year. The discount rate r represents the rate of return that could be achieved with a similar risky investment.

$$NPV = C_0 + \sum_i \frac{C_i}{(1+r)^i} \quad (1)$$

2.2 Component Failure Behavior

Within the maintenance, repair and overhaul business detailed information like date of installation or removal, number of flight cycles and flight hours of any single component is known. Even if a large number of data results from that, it is a sophisticated approach to generate valid distributions $F(t)$, distribution densities

$$f(t) = \frac{dF(t)}{dt} \quad (2)$$

or failure rates

$$\lambda(t) = \frac{f(t)}{1-F(t)} \quad (3)$$

for the lifetime of components.

On the one hand an analysis with the given information shows, that most common used distributions, e.g. normal, exponential or Weibull distributions, do not characterize the component failure behavior in a representative manner. Therefore parametric maximum likelihood estimation will not yield the approach of valid distributions and it is essential to use stochastic methods of nonparametric maximum likelihood estimation. On the other hand the derivative of that estimation method requires a balancing between preservation of statistical independence and availability of information about components failure behavior.

Against this background an algorithm was designed in [17], to calculate valid distributions with nonparametric maximum likelihood estimation for unscheduled events and not considering NFF events. Particularly in order to achieve feasible computing times and to

guarantee an appropriate size of the random sample, one distribution $F(t)$ were calculated for any component within ATA chapters with identical first three digits (ATA-3-digit chapter).

An exemplary distribution $F(t)$ and resulting distribution density $f(t)$ as well as failure rate $\lambda(t)$ are depicted in Fig. 1 Particularly with regard to the shape of the distribution density $f(t)$ the needfulness of using nonparametric maximum likelihood estimation becomes clear. Such distributions have been calculated for a wide number of ATA-3-digit chapters and form the basis for the following analysis in this study.

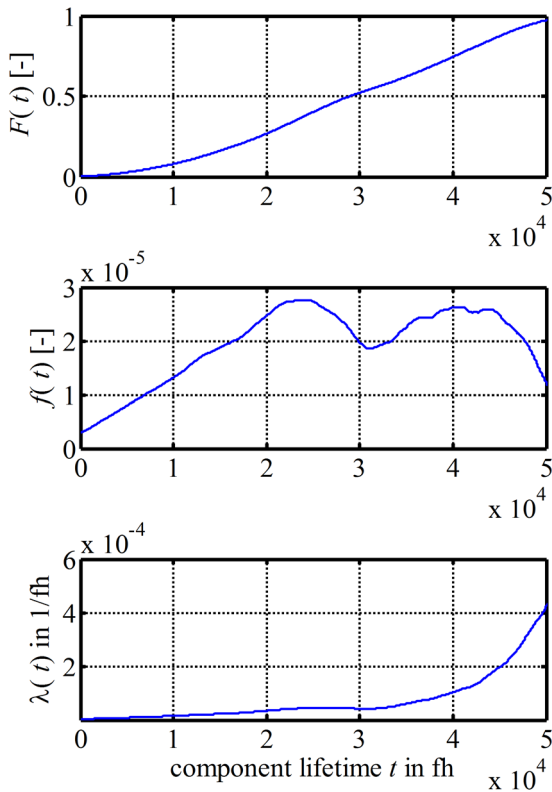


Fig. 1: Failure behavior of an exemplary ATA-3-digit chapter

2.3 Aircraft Lifecycle Simulation and Analysis

To capture time and cost aspects, the lifecycle cost-benefit model AirTOBS (Aircraft Technology and Operations Benchmark System) was developed.

AirTOBS models all economic relevant parameters along the aircraft life cycle. The aircraft operational lifecycle is initiated by the acquisition of an aircraft and ends with the decommissioning. The model includes aircraft specific parameters, operational aspects, e.g. route network or maintenance concepts, as well as global boundary conditions, e.g. fuel price trend. AirTOBS focuses on the perspective of an airline and includes methods to account for costs and revenues.

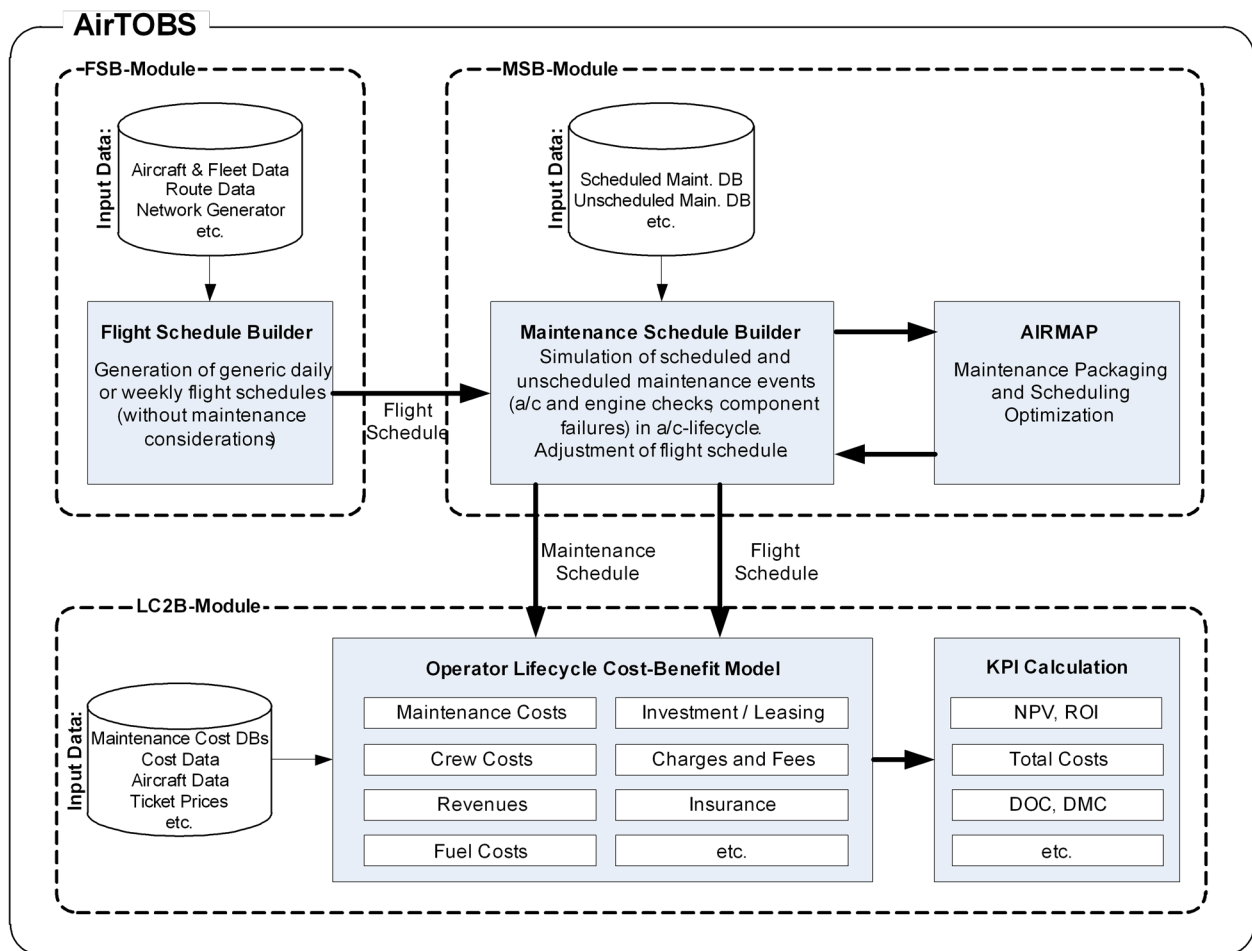


Fig. 2. Overview of aircraft lifecycle cost-benefit model AirTOBS

The model is generic in nature and is feasible for economic assessments of various aircraft technologies and operation concepts from an operator's or manufacturer's perspective. Apart from the assessment of prognostic concepts, studies on aircraft with natural laminar flow [18] or intermediate stop operation (ISO) concepts [19] have been conducted.

2.3.1 Structure of Lifecycle Cost-Benefit Model

An overview of AirTOBS is shown in Fig. 1. It consists of three main modules. The Flight Schedule Builder (FSB) generates a generic aircraft lifecycle flight schedule based on airline route data. Routes are considered based on the aircraft cycle time including flight time, taxi and runway operation times, and turnaround time. This provisional flight schedule serves as the fundament for the Maintenance Schedule Builder (MSB). The MSB executes a simulation

run of the flight operation and maintenance events over the aircraft lifecycle. The MSB uses input data from maintenance databases for the modeling of scheduled and unscheduled maintenance events, including airframe, engine and component maintenance.

The modeling of aircraft availability is based on a 24-hour day, reduced by night curfews at airports. The remaining time can be used for the planned flight operation including turnaround- and taxi-times.

Scheduled maintenance is considered depending on discrete, interval-based events. Intervals are specified by flight hours (FH), flight cycles (FC), and time (years, months, days). Each event has a specific ground time, during which the flight schedule is adjusted while producing time discrete costs to the airline. To account for operating experience and maturity effects in maintenance, maturity curves are provided within the model. The maintenance

schedule created by the MSB follows a traditional block check concepts for line and base maintenance.

2.3.2 Modeling of Unscheduled Maintenance

Unscheduled maintenance is considered on an aggregated ATA chapter level or by a provided component database. Using the modeled lifetime flight schedule, unscheduled events are simulated based on estimated component failure distribution functions, aircraft related mean times to repair (MTTR), e.g. time needed for replacement of a component or LRU.

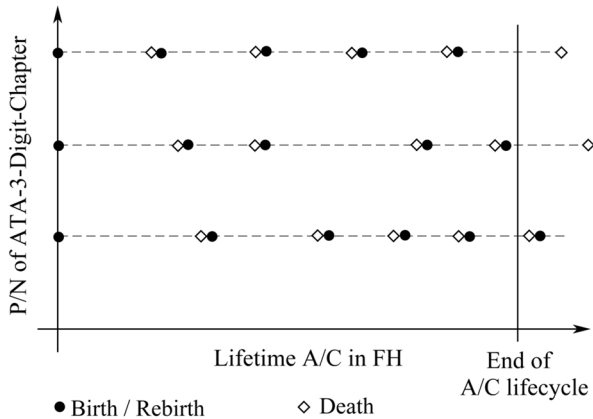


Fig. 4: Modeling of component lifetimes

For this study the MSB module uses component lifetimes randomly drawn from estimated nonparametric failure distribution functions $F(t)$ as are described in section 2.2. Unscheduled removals are modeled on an ATA-3-digit level over the aircraft lifecycle as shown in Fig. 4.

NFF events are modeled based on the NFF probabilities per FH that have been calculated from in-service data. The occurrence of an NFF event leads to an unscheduled removal of a component. The result is an early end of the current lifetime of a component, marked with a star in Fig. 3a. The beginning of the subsequent component lifetime is brought forward to the date of the NFF event, as shown in Fig. 3b. All

other future component lifetimes are pulled forward correspondently. The occurrence of PHM false alarms (marked with a cross) in the a/c lifecycle is modeled in the same way as an NFF.

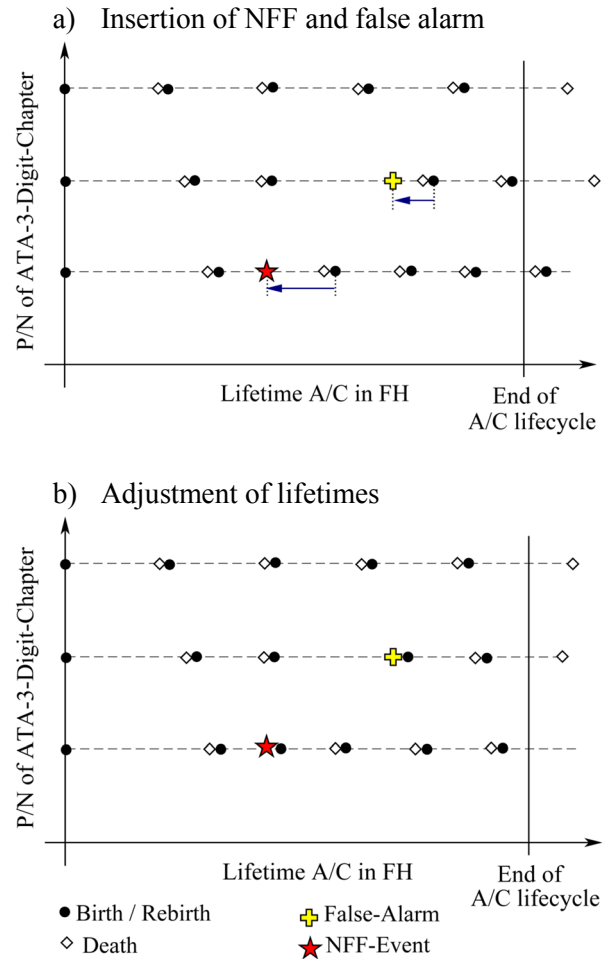


Fig. 3: Modeling of NFF events and false

Each failure that is initially covered by PHM can evolve into a missed failure with a certain probability (Fig. 5). A missed failure event has the same consequences as a failure not covered by PHM.

The probabilities of false alarm and missed failure events depend on the performance level of the PHM system and are input values of the model.

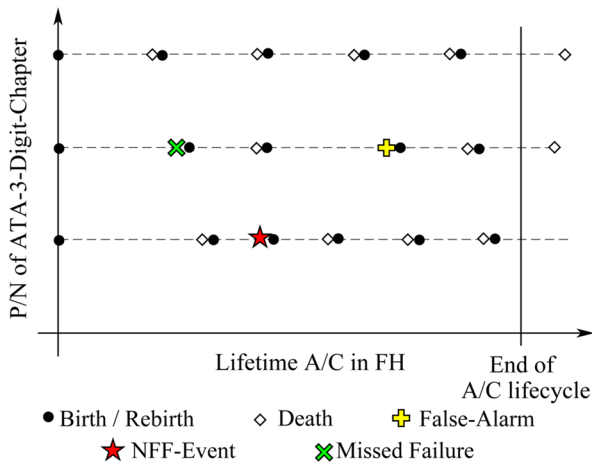


Fig. 5: Modeling of missed failures

Component removals produce costs for labor and material. Furthermore they can result in flight delays or cancellations depending on the minimum equipment list (MEL), the MTTR, and the planned aircraft turnaround time. Delays are modeled as a reduction in aircraft availability and a cost element that covers passenger compensations and accommodation.

Unscheduled failures not meeting the MEL-conditions can cause a flight cancellation when the remaining availability is not adequate to execute all planned flights of the respective day. In addition, a delay time threshold can be defined, which enforces a cancellation when a delay exceeds the threshold.

To consider the influences of maintenance strategies and component reliabilities on spare parts provisioning, related inventory costs are modeled. Overall LRU inventory costs are modeled based on estimated component quantities to meet a desired service level and the total carrying cost (capital and inventory cost). The estimated component quantities are calculated based on the aircraft utilization, quantities per aircraft, MTBURs, repair turnaround times and fleet size [20].

2.3.3 Modeling of Cash-Flows

After the maintenance schedule and the adjusted flight schedule are generated, the results are passed on to the Operator Lifecycle Cost-Benefit Model (LC2B), where costs and revenues are calculated (as shown in Fig. 1). Revenues are modeled using available statistics

with consideration of flight distances, seating classes, seat numbers and mean load factors. The actual time of occurrence of the cost and revenue elements is captured to account for the time value of money. The resulting cash-flows are escalated over the aircraft lifecycle to account for inflation, before they can be summarized as NPV.

3 Economic Lifecycle Analysis

A lifecycle analysis of a 150-seat short-range aircraft equipped with a PHM system is conducted in this study. First, relevant input data and assumptions are described. Then, the lifecycle analysis is conducted and the results are discussed.

3.1 Input Data and Assumptions

For this study, we have selected one exemplary aircraft system of a 150-seat short-range aircraft. The aircraft is operated by a full-service network carrier on a short range rotation with a daily utilization of 7.5 FH. Tab. 1 shows details of an assumed aircraft operation. The operating lifecycle is 25 years. We assume a traditional block-check maintenance program as shown in Tab. 3.

Tab. 1: Aircraft operational data

Parameter	Unit	Value
Operating days/week	[d]	7
Night curfew	[h]	7
Flights per day	[FC]	6
FH/FC		1.25
Taxi time	[h]	0.3
Turn-around-time	[h]	0.75
Block fuel	[kg]	4000

In order to be able to evaluate the monetary results, a summary of the relevant economic data used in the analysis are given in Tab. 2. The delay costs of 0.63 US\$ per passenger per minute include costs of passenger compensation and rebooking for missed connections, but also considers the costs of potential loss of revenue due to future loss of market share as a result of

lack of punctuality [21]. The internal rate of return r is assumed at 6.8 %.

Tab. 2: Economic data [21; 22]

Parameter	Unit	Value
Aircraft lifecycle	[years]	25
Internal rate of return r		0.068
Kerosene price	[US\$/gal]	0.34
Delay cost	[US\$/min/pax]	0.63
Average inflation	[1/year]	0.0194

Additional assumptions are made regarding the maintenance processes. Each component removal modeled as a separate unscheduled event with a potential delay consequence. The authors have indications that in reality typically more than one component is replaced during an unscheduled event. This effect will be considered in future studies.

3.2 Economic assessment in AirTOBS

Since AirTOBS is a discrete event-simulation of an aircraft lifecycle, it produces deterministic results. As mentioned before component failure behavior, consequences of unscheduled maintenance events and successful failure predictions are substantially based on stochastic processes. In order to account for these uncertainties, a Monte Carlo simulation is implemented in AirTOBS. Stochastic inputs are generated randomly from individual probability functions. Afterwards the deterministic lifecycle simulation is run with the random inputs. In the end, the results are aggregated and prepared for presentation and interpretation.

Usually very large numbers of simulations are selected, when coping with uncertainties in a discrete-event simulation (depending on type

Tab. 3: Typical scheduled maintenance data of a short-range aircraft [2]

Name	Downtime [h]	Intervals				Man-hours	Material cost [US\$]
		Flight hours [h]	Flight cycles	Days	Months		
Weekly	-	-	-	7	-	10	700
A-Check	24	600	-	-	-	80	5,500
C-Check	138	-	-	-	18	2,000	28,500
IL-Check	336	-	-	-	72	14,300	380,000
D-Check	672	-	-	-	144	20,000	1,500,000

Furthermore, it is assumed that all components that are part of the study are subject to a reactive maintenance strategy and are not subject to any hard-times. This is not necessarily correct for all examined items.

Costs for development, implementation and operation of a PHM system are not included in this study. The goal is to provide economic results that allow deriving acceptable costs of a prognostic system for a specific aircraft system.

The analysis is based on in-service data from 58 ATA-3-digit chapters of the examined fleet. For this study, one specific ATA chapter (with related ATA-3-digit chapters) is selected. NFF rates, MTTRs, repair cost and ratio of 'NO GO'-items and 'GO IF'-items are known for each of the 58 ATA-3-digit chapters.

and form of underlying distribution functions), in order to receive stable and statistically significant results. In this study we chose to calculate only 100 simulations for each point in the parameter space. The selected number of calculations shall represent a fleet of 100 aircraft operated by a single airline. Through this approach, the results reflect the uncertainties an aircraft operator will be confronted with, when using PHM systems.

To analyze the impacts of PHM performance parameters and coverage rates a parameter variation is conducted. In addition to PHM related parameters the lifetimes of the components in the selected ATA chapter are varied to account for increasing or decreasing component reliabilities.

Tab. 4: Parameter space for analysis

Parameter	Values				
PHM coverage	0 %	25 %	50 %	75 %	100 %
False alarms [1/FH]	0	5.0e-6	1.0e-5	2.5e-4	5.0e-4
Missed failure rate	0	0.05	0.1	0.2	0.3
Lifetime variation	-20 %	-10 %	0 %	10 %	20 %

The parameter space for the analysis is shown in Tab. 4. For each point in the parameter space, the Monte-Carlo simulations are conducted. This is followed by an aggregation of the results.

3.3 Analysis Results

The impacts of PHM on unscheduled maintenance and aircraft operation are shown first. Then, the economic results from an airline perspective are presented. These results are also relevant for aircraft manufacturers and MROs as airlines are their customers.

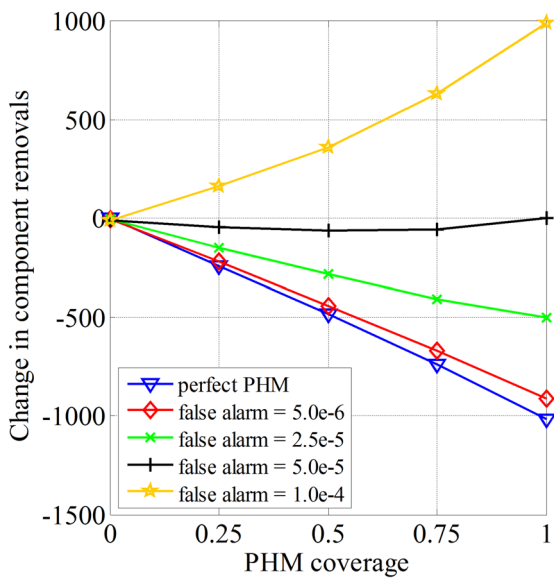


Fig. 6: Change in unscheduled component removals in a/c lifecycle

All diagrams shown below describe operational or monetary results as a function of the PHM coverage rate² from 0 to 1, with 0

² The PHM coverage rate describes the portion of failures for which a specific prognostic system can report

reflecting the reference case without PHM use. Each diagram contains five different graphs to reveal the impact of varying false alarm or missed failure rates.

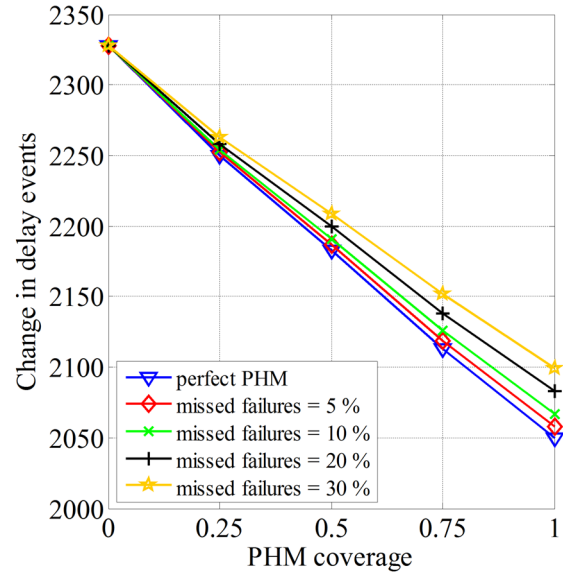


Fig. 7: Technical delays in a/c lifecycle

Fig. 6 depicts the change in unscheduled component removals in a/c lifecycle due to the PHM implementation for a selected ATA chapter. In this study, a use of PHM leads to a

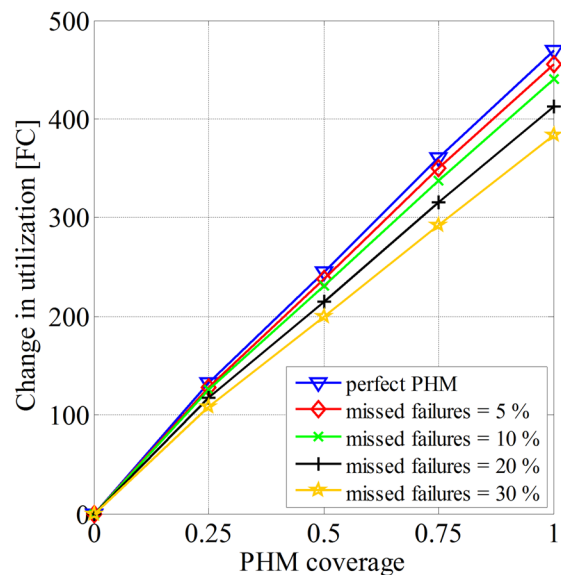


Fig. 8: Change in a/c utilization

reduction of unscheduled events in a/c lifecycle by 1000 in the optimal case (i.e. use of a perfect

imminent failures, without consideration of false alarms and missed failures.

PHM). Depending on the false alarm rate, the reduction can be smaller or the number of component removals can even increase with high false alarm rates (Fig. 6). The reason for the change in the total number of events lies solely in the reduction of NFFs on the one side and the generation of additional events caused by false alarms on the other side. The missed failure rate has no effect on the number of component removals.

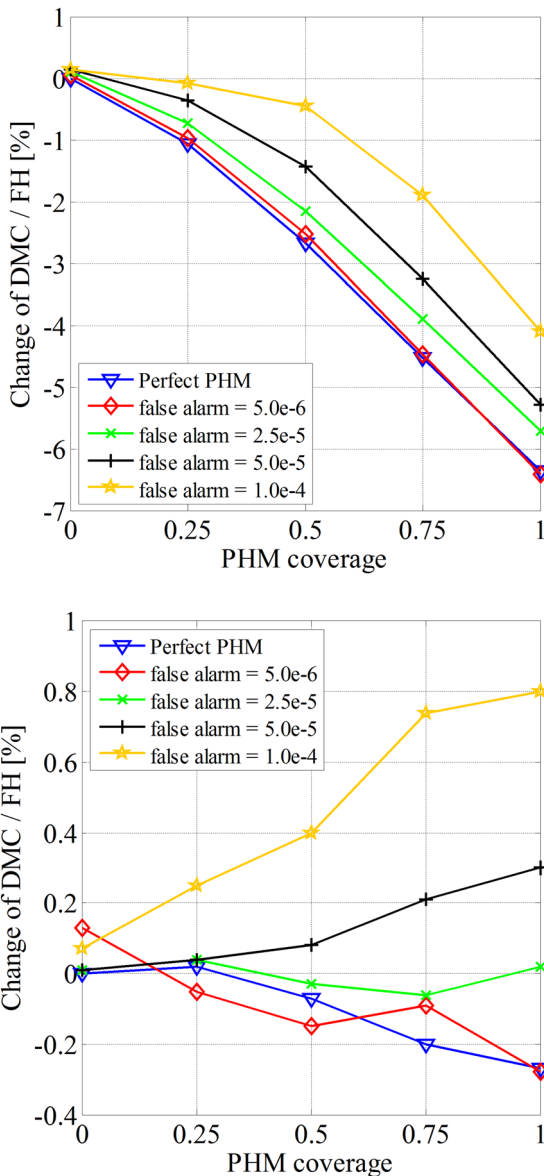


Fig. 9: Change of a/c DMC for a PHM use in two different systems

As mentioned before, an unscheduled event results in a technical delay, when a failure (or NFF) is not covered by a PHM system, the failure is classified as ‘No Go’, and MTTR

exceeds the available time during a/c turnaround. It can be seen from Fig. 7 that the number of technical delays can be reduced by 230 to 280 depending on the missed failure rate of the PHM system.

The reduction of delay events results in additional revenue flights in aircraft lifecycle, as shown in. An increase of utilization by 470 FC (equivalent to 0.94 % of total flight cycles) can be achieved in case of a perfect PHM system and a coverage rate of 1. With a missed failure rate of 30 %, a maximal additional utilization of 380 FCs can be realized (Fig. 8).

While total operating and maintenance cost in a/c lifecycle can increase due to an increase in utilization, an appropriate metric to evaluate the effect of PHM is Direct Maintenance Cost (DMC) per FH. The relative change of DMC/FH for varying false alarm rates is presented in Fig. 9. Significant reductions in maintenance cost are only achievable with high PHM coverage rates, while the benefits can be diminished considerably by high false alarm rates (Fig. 9, top). In other cases (i.e. different aircraft systems), even medium false alarm rates can cause increasing DMC (Fig. 9, bottom). The comparison of the two diagrams shows clearly that the effects of PHM depend on the characteristics of the individual aircraft system.

The overall net-benefit of PHM is described by the change in NPV. Under the

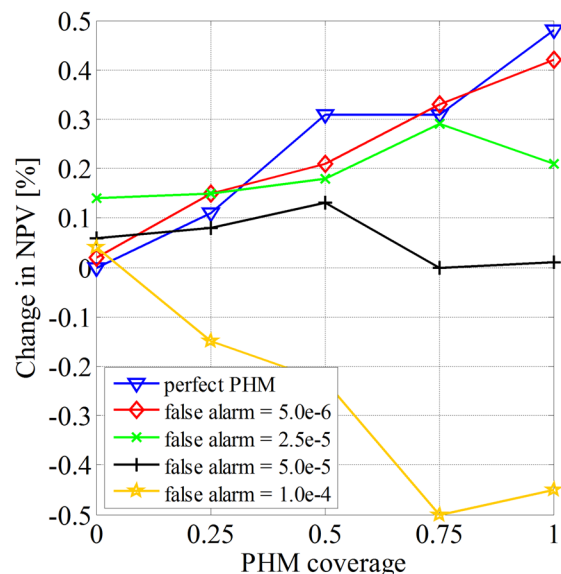


Fig. 10: Change in NPV

assumptions made in this study, an increase in NPV up to 0.48 % can be obtained in the case of full PHM coverage and a perfect PHM system (Fig. 10). No benefits can be realized with medium or high false alarm rates. Furthermore, it has to be kept in mind, that a complete coverage of an aircraft system by PHM is a theoretical goal. Most likely, it is not achievable due to technological and economic limitations.

Since each of the analysis results is a mean value of 100 simulations (corresponding with the assumed fleet size) the values are subject to significant variances. This can clearly be seen in Fig. 10. An aircraft operator with a comparable fleet size can expect similar variances of the effects of a PHM system due to the stochastic nature of the technical failure behavior.

4 Conclusion and Outlook

In this study potential benefits and drawbacks of a PHM implementation from an airline's perspective are analyzed. It is demonstrated that a methodology is available that allows an economic assessment of PHM depending on the technology under investigation (i.e. on ATA-3-digit level).

Therefore, an algorithm for the calculation of estimated nonparametric component failure distribution functions was developed. The distribution functions are calculated from in-service data and integrated in the aircraft lifecycle cost-benefit model AirTOBS to evaluate the impacts of a PHM use in current aircraft. The model takes into account all relevant effects of PHM on the aircraft operation and maintenance, including false alarms and missed failures.

Benefits by a PHM implementation can only be expected, if a very detailed examination is made. It is essential for all stakeholders to look in detail, which systems can be appropriate for a PHM use from an economic point of view. When the highest potentials on aircraft system level are identified, an analysis on single component level has to follow.

For future studies, the used methodology should also calculate the variance of results when conducting a Monte Carlo simulation.

This would enhance the assessment of uncertainties associated with PHM use.

While in this study, a short-range operation by a network-carrier is assumed, different concepts of aircraft operation and variable rotation plans should be considered in further studies. In addition, line maintenance and maintenance planning processes should be modeled in a more detailed way to capture further interactions between aircraft operation and maintenance.

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