Cost-benefit Analysis of Prognostics and Condition-based Maintenance Concepts for Commercial Aircraft Considering Prognostic Errors

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ABSTRACT

This paper provides a lifecycle cost-benefit analysis of the use of Prognostics and Health Management (PHM) systems in future or present commercial aircraft. The approach considers individual aircraft component's failure behavior, prognostic performance levels including prognostic errors, and condition-based maintenance (CBM) concepts. The proposed methodology is based on a discrete-event simulation for aircraft operation and maintenance and uses an optimization algorithm for the planning and scheduling of condition-based maintenance (CBM) tasks. In the study, a 150-seat short-/medium-range aircraft equipped with PHM and subject to a CBM program is analyzed. The simulation results are evaluated from an operational and economic perspective. The analysis results can support the derivation of technical and economic requirements for prognostic systems and CBM planning concepts.

1. BACKGROUND

In general, prognostic systems provide early detection of the precursor (and/or incipient) fault condition of a component and are capable to predict its remaining useful life (RUL) (Engel et al., 2000). In addition, the fault isolation and identification capabilities of PHM contribute to a reduction of no-fault-founds (NFFs) and support the trouble shooting process (Leao et al., 2007). The implementation of PHM in commercial aircraft can help to reduce operational interruptions due to unscheduled maintenance events.

Significant reductions in maintenance downtimes and costs can be obtained when today's periodic, preventive maintenance is transformed towards a predictive (i.e. condition-based) maintenance strategy. The major expected benefits in this case are substitutions of preventive inspection tasks and reductions of waste of (component-) lives. This will lead to reductions of overall maintenance cost and downtimes. These benefits are also known as the realization of maintenance credits.

But a CBM concept leads to an increased planning complexity and therefore requires a different maintenance planning approach in order to achieve the aimed goals of a PHM and CBM implementation (Hölzel et al., 2014).

Besides the solving of technical challenges of prognostics 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 all relevant impacts of the technology on aircraft operation and maintenance over the aircraft lifecycle.

Economic assessments of PHM applications have been discussed by many authors (e.g. Banks et al., 2005; Feldman et al., 2009; Leao et al., 2007; Sandborn & Wilkinson, 2007; Scanff et al., 2007). Typical measures are lifecycle costs (LCC) or return-on-investment (ROI) estimates of the implementation costs and the potentials for cost avoidance (e.g. Banks et al., 2005). Leao et al. (2007) developed a cost-benefit analysis (CBA) methodology for PHM applied to legacy aircraft. Their approach is capable to conduct assessments from an aircraft manufacturer's or operator's perspective, but it requires many inputs from technical analyses and PHM specialists. Sandborn and Wilkinson (2007) have proposed a lifecycle cost approach which includes a maintenance planning model and considers various uncertainties with regard to PHM systems. While the model provides a detailed picture of the usefulness of PHM on component or sub-system level, it does not cover additional impacts and interactions on overall system (i.e. aircraft) level.

Both levels of analysis, component and overall system level, are needed, when a profound CBA of PHM with particular attention on the implementation of CBM should be provided. A cost-benefit approach has to cover the relevant impacts of PHM on component or sub-system level and should consider the corresponding uncertainties. This component level must then be integrated on aircraft level, in order to analyze the effects of PHM and CBM in a realistic aircraft operation scenario.

In real world applications, no prognostic system will operate completely perfect. Therefore, uncertainties and prognostic performance levels including probabilities of false prognoses (false positives) and missed failures (false negatives) have to be considered (Saxena et al., 2010). Previous analyses have shown that the prognostics performance level has a significant impact on the added value of a PHM system (Hölzel et al., 2012).

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. This is true for the assessment of PHM, since new maintenance concepts influence maintenance cost and aircraft availability (and thereby aircraft utilization). The use of a discounted cash-flow method is required to take into account the time value of money when assessing an aircraft or technology concept over its entire lifecycle.

The overall benefits of a PHM application depend on the criticality of the monitored item (in terms of safety and operational reliability of the aircraft), the prognostic performance levels and both the current and novel maintenance concept. Therefore, a detailed modeling and analysis of all relevant factors and economic conditions is needed.

2. GOAL OF STUDY

The goal of this study is to propose an appropriate method for analyzing the economic potentials of a PHM and CBM implementation in existing and future commercial aircraft. The applied methodology should facilitate informed decision making in the design or acquisition phases of PHM systems.

The applied approach should consider all phases in aircraft lifecycle and include the following benefits of PHM deriving from the capability to provide advanced warnings of failures and predictions of the RUL:

1. Reduction of unscheduled maintenance events due to failures (and NFFs) of items/components.
2. Enabling CBM: Transition from preventive to condition-based maintenance measures.

To consider uncertainties in component failure behavior, the methodology used in the study should be based on individual component failure probability functions. Prognostic errors (i.e. false alarm rates and missed failure rates) have to be included to account for imperfect sensors or prognostic algorithms. The selected approach should be able to simulate the impacts of PHM systems and a CBM concept in a realistic aircraft operation scenario. The simulation results are then evaluated in a lifecycle cost-benefit model.

The approach is demonstrated in a case study to show the potential economic benefits of a PHM/CBM concept from an airline perspective including possible prognostic errors and uncertainties in technical failure behavior.

3. METHODOLOGY

This chapter gives an overview of the generic aircraft lifecycle analysis method used for this study and describes the specific assessment approach for the CBA of PHM and CBM concepts.

3.1. Aircraft Lifecycle Analysis Approach

At DLR, the lifecycle cost-benefit model AIRTOBS (Aircraft Technology and Operations Benchmark System) was developed to enable a holistic economic assessment of aircraft technologies[1] already in a conceptual design phase.

The model captures time and cost aspects in aircraft lifecycle, is generic in nature and is feasible for economic assessments of various aircraft technologies and operation concepts from an operator's perspective. Apart from the assessment of prognostic concepts (Hölzel et al., 2012; Hölzel et al., 2014), studies on aircraft with natural laminar flow (Wicke et al., 2012) or intermediate stop operation concepts (Langhans et al., 2010) have been conducted.

It 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 (e.g. acquisition cost, fuel consumption, seating capacity, crew size, and aircraft specific charges), operational aspects (e.g. route network, maintenance concepts and costs, and ticket prices), as well as global boundary conditions (e.g. fuel price trend, annual inflation rate). AIRTOBS focuses on the perspective of an aircraft operator and includes methods to account for costs and revenues.

An overview of AIRTOBS is shown in Figure 1. It consists of three main modules. The Flight Schedule Builder (FSB) generates a generic aircraft lifecycle flight schedule based on airline route data assuming full aircraft availability (i.e. no maintenance). Routes are considered based on the aircraft cycle time including flight time, taxi and runway operation times, and turnaround time. This flight schedule has the character of a basic mission plan for a single aircraft. It does not include any maintenance downtimes.

[1] In this context, the term technologies can represent aircraft, systems, components, or aircraft operational and maintenance concepts.

The mission plan serves as the fundament for the Maintenance Schedule Builder (MSB). The MSB executes a discrete-event simulation of the flight operation and maintenance events along 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 Lifecycle Cost-Benefit (LC2B) module calculates all costs and revenues on the basis of the simulated aircraft operation and maintenance using pre-defined cost and revenue models. All values are escalated over the aircraft lifecycle to account for inflation, before they can be summarized as net present value (NPV). 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 equivalent investment alternatives in the capital market (Brealey, Myers, & Franklin, 2006). In business practice, a company or industry weighted average cost of capital (WACC) is often used as discount rate.

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

The NPV is one among many other metrics that are calculated in AIRTOBS and can be used for the comparative evaluation of aircraft technologies and operational concepts.

The presented simulation and assessment tool AIRTOBS is modeled in MATLAB©. Each module requires specific input data and can be configured with regard to analysis goals and needs. Aircraft type and operator specific XML-files are used to configure and control the analyses.

3.2. Applied Assessment Approach

The economic analysis in this paper follows the assessment approach as outlined in Figure 2. At its core, the approach is based on the discrete-event simulation of aircraft operation including the optimization algorithm for maintenance planning provided by AIRTOBS. The desired economic performance indicators are calculated with the LC2B module.

A CBA is realized by comparing the system under assessment (i.e. aircraft equipped with PHM and subject to a CBM program) with a pre-defined baseline (i.e. reference aircraft without PHM and subject to a conventional maintenance program).

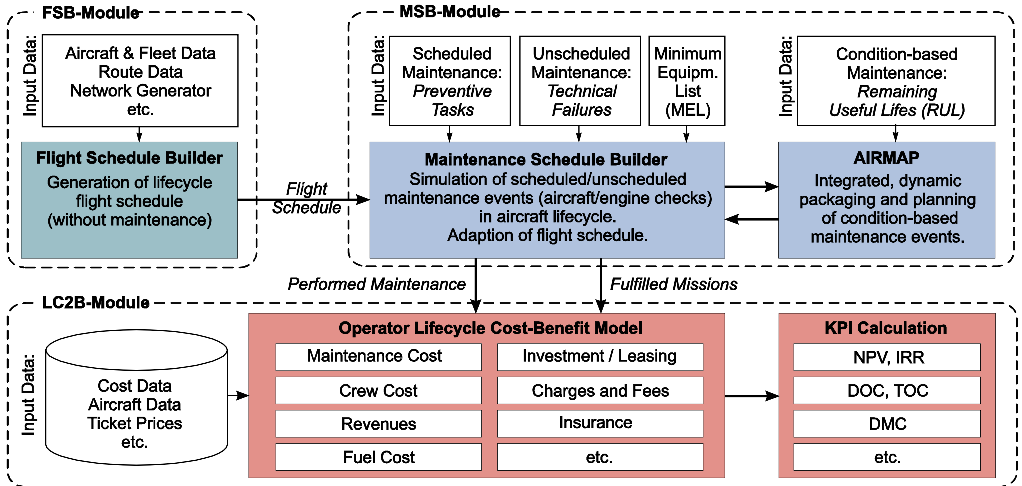


Figure 1. Architecture of lifecycle cost-benefit model (operator modules).

The analysis requires a large amount of input data:

- PHM system: specification of covered failure modes of sub-systems or components, corresponding prognostic performance levels and costs,
- Reference aircraft: aircraft data, scheduled maintenance program, MEL, component failure behavior, etc.,
- Maintenance capacities at considered airports: number of mechanics, hangar slots, capabilities, etc.,
- Flight schedule and aircraft rotation plan,
- Operational and boundary conditions: ticket prices, labor cost, inflation, etc.

Based on the specified PHM system and a selected aircraft with its corresponding failure probability density functions (PDFs) a lifecycle simulation of technical failures is conducted. This process results in RUL values (in case of a successful prognosis) and the generation of unscheduled maintenance events (in case of failure not predicted by the PHM system).

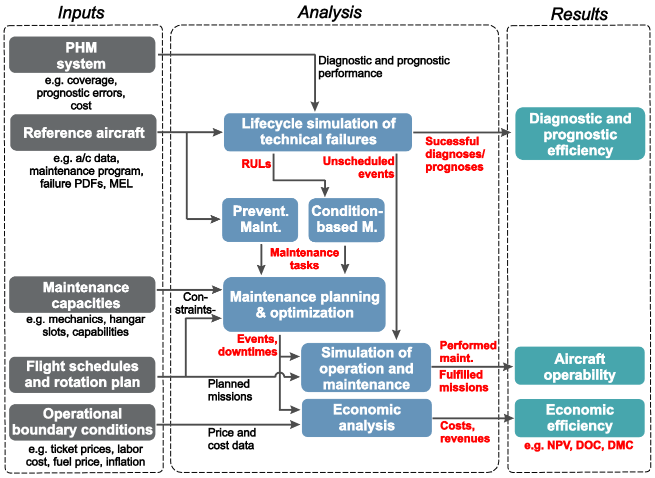


Figure 2. Applied assessment approach.

Preventive maintenance tasks derived from the aircraft's maintenance planning document (MPD) and CBM tasks initiated by the estimation of RULs are subject to an integrated maintenance planning and optimization process. Available maintenance capacities at different airports, the planned flight missions and rotation plan form the constraints of the optimization problem. The optimizer identifies a valid and efficient maintenance plan.

The planned flight missions are derived from a flight schedule (generated by the FSB module for a selected airline's operation concept).

The discrete-event simulation then models the flight operation and maintenance in aircraft lifecycle based on simulated unscheduled events and calculated scheduled (preventive and condition-based) maintenance events and the corresponding aircraft downtimes.

Finally, the overall economic analysis is conducted using the LC2B module of AIRTOBS.

Parametric studies will show the sensitivities of prognostic performance levels, CBM implementation and maintenance planning constraints with regard to the benefits of an operator's point of view. From these studies, it is possible to derive essential requirements for prognostic systems and CBM concepts, e.g. minimum performance levels, maximal costs for acquisition and operation and minimum maintenance capacities, under given conditions.

3.3. Modeling of Maintenance Events and PHM Impacts

This section describes the modeling of maintenance events and the logic how the impacts of PHM on scheduled and unscheduled maintenance are implemented in the MSB module as depicted in Figure 1. The maintenance modeling is realized as discrete-event simulation based on the planned flights in aircraft lifecycle.

3.3.1. Scheduled Maintenance

Scheduled maintenance is considered depending on discrete, interval-based events. Intervals are specified by flight hours (FH), flight cycles (FC), and calendar 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 concept for heavy maintenance. Line maintenance checks are modeled on task-oriented basis and can thereby be subject to a dynamic planning process.

3.3.2. Unscheduled Maintenance

An unscheduled event is characterized by a technical failure and/or a fault message (of a diagnostic system), fault report (of crew or maintenance), or a finding (due to an inspection). It can be followed by one or more component removals taking place in aircraft line maintenance. A component removal results in a shop maintenance event and the installation of an airworthy (new or repaired) component.

Modeling of unscheduled maintenance requires knowledge of the failure behavior of the respective components or systems. When sufficient historic data are available, (parametric or non-parametric) failure distribution functions can be calculated (Hölzel et al., 2012). The presented approach uses discrete component lifetimes randomly drawn from the estimated failure distribution functions to model unscheduled removals on component or sub-system level over the aircraft lifecycle (Figure 3).

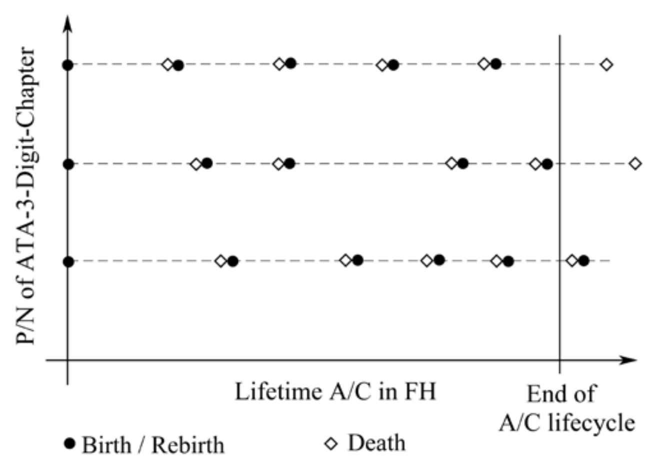


Figure 3. Modeling of component lifetimes.

Particularly in order to attain feasible computing times in the following simulation process and to guarantee an appropriate sample size, one distribution function was calculated for any component within ATA Chapters with identical first three digits (ATA 3D Chapter, i.e. sub-system level) (Hölzel et al., 2012).

NFF[2] 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 component removal. The result is an early end of the current lifetime of a component, marked with a star in Figure 4 a. The beginning of the subsequent component lifetime is brought forward to the date of the NFF event, as shown in Figure 4 b. All other future component lifetimes are pulled forward correspondently (Hölzel et al., 2012).

Using the previously (by the FSB module) created lifetime flight schedule, unscheduled events are simulated based on component failure behavior, aircraft related mean times to repair (MTTR) and maintenance man-hours, i.e. downtime and man-hours needed for replacement of a component or LRU. 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.

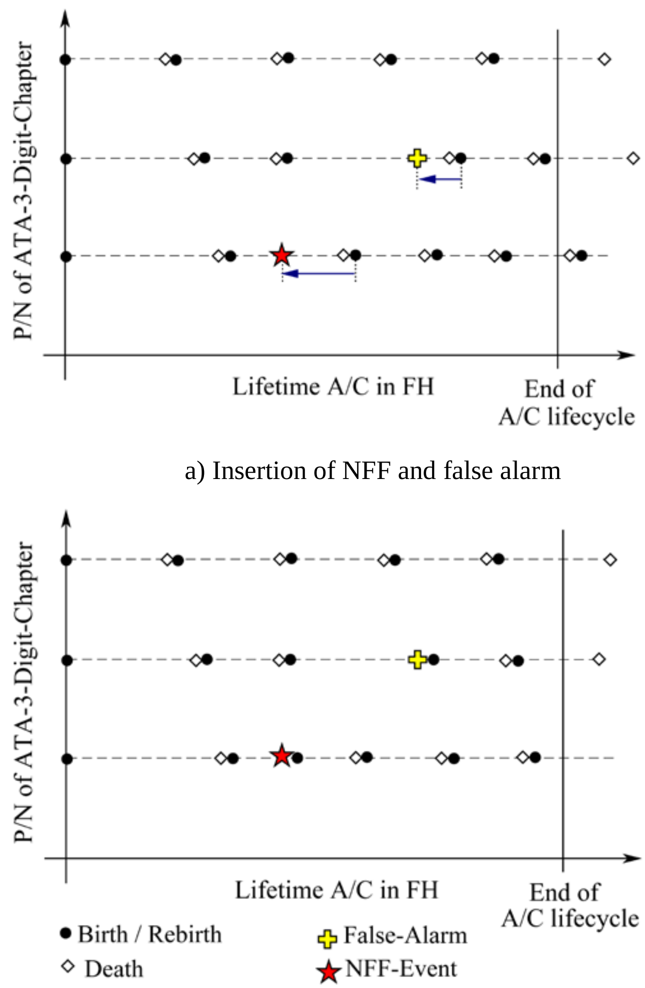
To consider the influences of maintenance strategies and component reliabilities on spare parts provisioning, related inventory costs are modeled. Overall LRU inventory costs are modeled based on estimated component quantities to meet a desired service level and the total carrying cost (capital and inventory cost). The estimated component quantities are calculated based on the aircraft utilization, quantities per aircraft, mean times between unscheduled removals (MTBURs), repair turnaround times, and fleet size (Khan et al., 1999).

3.4. Impacts of PHM and Prognostic Errors

An implementation of prognostics in aircraft systems can lead to a variety of operational and economic benefits as described before. In this study, the following benefits of PHM are in focus:

1. Reduction of unscheduled events due to failures (and NFFs) of items/components.
2. Enabling CBM: Transition from preventive to condition-based maintenance measures with corresponding influence on aircraft downtimes and maintenance cost.

The underlying effect mechanisms of prognostics on aircraft maintenance are modeled in different ways.



a) Insertion of NFF and false alarm

b) Adjustment of lifetimes

Figure 4. Modeling of NFFs and prognostic false alarms.

Impending failures that are successfully predicted by the prognostic system no longer result in unscheduled events. Instead, a CBM task is generated with the estimated RUL as latest due date. Those CBM tasks are subject to the maintenance planning process described in the following section 3.5. It is assumed that NFF events of components monitored (covered) by PHM can be avoided completely.[3]

Depending on the prognostic performance level (described in a PHM model) an impending failure can be detected

[2] An item removal is classified as NFF when no fault is exhibited during subsequent acceptance test (James et al., 2003).

[3] In reality, there are many different reasons for NFF events. It is expected that only a portion of these events can actually be prevented by the use of PHM.

successfully, or it may be missed. Two types of prognostic errors are taken into account:

1. False alarm: Prognostic system detects an impending failure, although no failure is impending, or system reports impending failure early.
2. Missed failure: Prognostic system does not detect an impending failure or detects it late.

The modeling of prognostic errors is shown in Figure 4 and Figure 5. The occurrence of PHM false alarms (marked with a cross) in the a/c lifecycle is modeled in the same way as an NFF. Each failure of an item that is initially covered by PHM [4] can evolve into a missed failure with a certain probability (Figure 5). A missed failure event has the same consequences as a failure not covered by PHM.

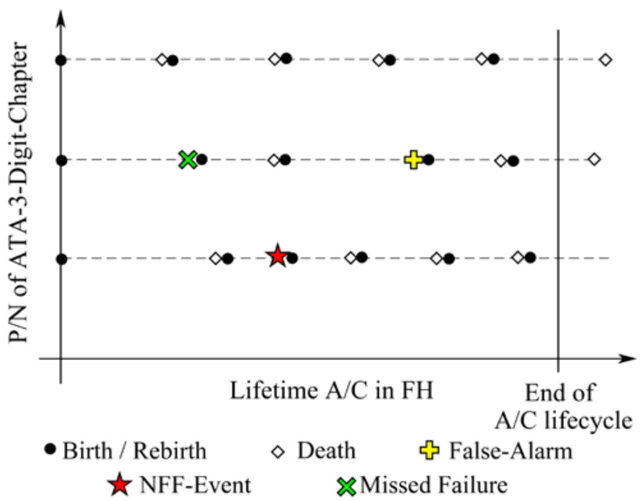


Figure 5. Modeling of missed failures.

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. The operational consequences of an undetected failure are modeled based on the MEL and the planned flight operation.

The potential impact of PHM on preventive, scheduled maintenance tasks depends on its task code. Scheduled maintenance tasks can be assigned to a variety of different task codes (Airbus, 2007) as listed in Table 1. While tasks with some task codes could become obsolete if a PHM system is used, prognostics have no influence on other scheduled tasks listed in the scheduled maintenance program (MPD).

[4] It is assumed that an individual PHM system is designed to detect certain (incipient) fault conditions. Due to different uncertainties in detecting the correct fault condition and predicting the RUL it may occur that the prognostic algorithm misses an impending failure.

For the sake of simplification and generalization, the task codes are summarized to six task code groups (TCG) within the model as shown in Table 2. TCG 1 to 3 reflect tasks, which are potentially redundant (obsolete), if a PHM system covers the contained tasks. It is assumed that the prognostic system is able to automatically carry out a certain fraction of the check- or inspection-tasks in a continuous or non-continuous manner. The fraction of tasks covered by a PHM system can be adjusted with the task redundancy parameter P_{TR}. The parameter P_{TR} implies that it is possible to eliminate the corresponding scheduled maintenance task from the MPD under consideration of certification requirements.

Table 1. Maintenance task codes.

Task Code	Definition
BSI	Borescope inspection
CHK	Check for condition, leaks, circuit continuity, check fluid reserve on item, check tension and pointer, check fluid level, check detector, check charge pressure, leak check/test.
DI	Detailed inspection
DS	Discard
FC	Functional check/test
GVI	General visual inspection
LU	Lubrication
OP	Operational check/test
RS	Remove for restoration
SDI	Special detailed inspection
SV	Drain, servicing, replenishment (fluid change)
TPS	Temporary protection system
VC	Visual check

Table 2. Task code groups and potential PHM impact.

Task code Group (TCG)	Included task codes	Potential impact of PHM
TCG 1	CHK, OP, FC	Task elimination
TCG 2	GVI	Task elimination
TCG 3	DI, SDI	Task elimination
TCG 4	SV, DS, RS	Interval escalation
TCG 5	Non-routine	Interval escalation
TCG 0	Non-routine / other	No impact

If a significant fraction of scheduled tasks can be eliminated through a PHM implementation, this reduces the total workload and potentially also the aircraft downtime of a maintenance check. Without special consideration of the minimum duration of certain tasks (“shortest path”), the influence of PHM on aircraft downtimes can be estimated as shown in Eq. (2).

$$t_{DT,new} = t_{DT,0}\left(1 - P_{TR} \cdot r_{routine} \cdot r_{TR}\right) \quad (2)$$

$t_{DT,new}$ resulting maintenance downtime

$t_{DT,0}$ maintenance downtime without PHM impact (reference case)

P_{TR} task redundancy parameter

r_{TR} ratio of routine tasks potentially redundant in case of PHM use

$r_{routine}$ ratio of routine task man-hours to complete man-hours of check

It is assumed that preventive maintenance tasks related to TCG 4 have to be carried out less frequently when the corresponding items are monitored by PHM. This means, the former limited service life of the item is extended through the use of PHM depending on the actual condition. Since no component degradation models are available for this study, the influence of PHM on service life is modeled with the interval escalation parameter P_{IE}, which is assumed as input value and can be varied in a parameter variation.

In addition to routine activities, scheduled checks also comprise large amounts of non-routine tasks. Detected findings result in non-routine activities (i.e. repairs or replacements of the respective items), when the degradation may reach a critical state prior to the next preventive inspection. It is assumed that a certain part of these non-routine tasks can be conducted at a later time, the respective items are subject to a CBM strategy (and monitored by PHM). These tasks are summarized in TCG 5. The last task code group (TCG 0) includes non-routine (e.g. findings that are critical for flight safety and thus have to be repaired immediately) and other tasks (e.g. cabin refurbishments and paintings) to which a PHM system has no influence.

3.5. Condition-based Maintenance Planning

The planning of aircraft maintenance is the allocation of maintenance tasks (i.e. objects) that must be carried out on specific aircraft to maintenance capacities (i.e. bins). Combinatorial problems of this character are of higher complexity and are very similar to the elementary bin-packing problem (Fukunaga et al., 2007; Bohlin, 2010). Since the aircraft maintenance planning, as discussed in this paper, considers more variables and constraints as the “simple” bin packing problem, it is very likely to be NP-hard [5]. Although the problem might not be solved in polynomial time, solutions can efficiently be verified, e.g. by using a branch-and-bound algorithm (Korte et al., 2006; Schröder, 2011).

In the proposed approach, each ground time of an aircraft (turnaround times and overnight stays) is regarded as a maintenance opportunity. It is the goal to minimize aircraft maintenance costs and to utilize existing maintenance opportunities efficiently while aircraft rotation planning and limited maintenance capacities are considered. This is achieved by appropriate grouping (packaging) of maintenance tasks, while considering technical (maintenance intervals or RULs determined by a PHM system) and organizational restrictions. The process of task packaging reduces the number of maintenance events and allows an efficient use of maintenance opportunities. But it leads to waste of life when items are maintained earlier than required or tasks are performed before due date (Hölzel et al., 2014).

In this study, preventive scheduled and condition-based maintenance activities are subject to the maintenance planning optimization. The maintenance optimization is designed as a dynamic planning approach that responds to varying maintenance needs and airline operation during aircraft lifecycle. This is achieved by splitting the operating lifecycle into shorter planning periods (e.g. four or eight weeks) that are run through sequentially. Compared to a single optimization covering the complete lifecycle, this procedure leads to a significantly reduced computation time (due to the reduction of the optimization problem) and reflects the reality in a better way.

The CBM planning function is implemented in the AIRMAP module (as shown in Figure 1). AIRMAP is based on a mathematical formulation of the maintenance planning problem as described in Hölzel et al. (2014). The planning problem has been formulated on a fleet level to model the competition of a number of aircraft for limited maintenance resources. The applied optimization approach can be characterized as depth-first-search branch-and-bound algorithm. The resulting task packaging and maintenance scheduling process is illustrated in Figure 6. The figure shows due dates (marked with an “X”) for a number of tasks (“Task 1” to “Task n”) in two random periods in aircraft life. For each planning period, the algorithm searches for a cost-minimal maintenance plan in an iterative process. The resulting maintenance events are marked with vertical dotted lines. The distances between the time of an event and the due dates of the allocated tasks represent the waste of life (expressed in FH). Due to the limitation of maintenance capacities and individual costs and man-hours of the tasks, it can be feasible to allocate a task to an event other than the nearest (e.g. allocation of second due date of “Task 5” to “Event 2” in Figure 6).

It is possible that the optimizer cannot allocate tasks, which are due shortly after the beginning of a new period because of a lack of maintenance opportunities. To avoid this, the user of the optimizer can define a buffer period that forces the algorithm to allocate the respective tasks in the preceding period (e.g. the third execution of “Task 1” is allocated to “Event 3” in Figure 6).

The optimizer plans maintenance events for planning periods sequentially (beginning with aircraft entry into service). The algorithm takes into account only those tasks

[5] NP-hard describes a class of problems in computational complexity theory.

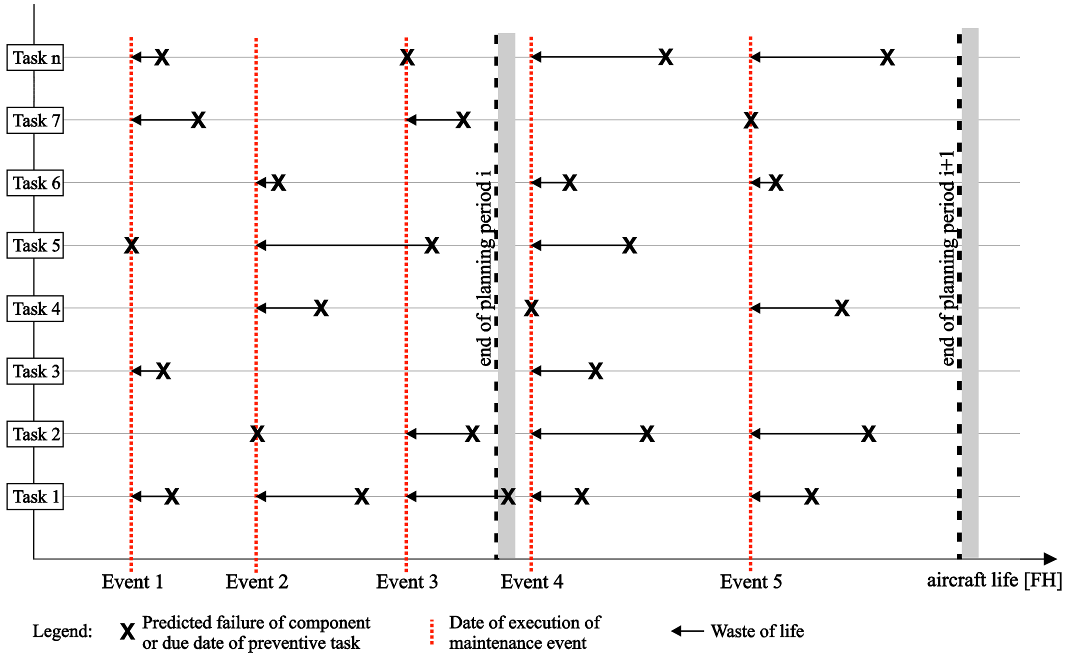


Figure 6. Maintenance scheduling and task packaging.

that are due in the current planning period. All other tasks are moved to the next planning period.

AIRMAP submits the best plan found to the MSB module (as depicted in Figure 1), which then simulates the performed maintenance events and fulfilled flight missions over the complete aircraft lifecycle schedule as basis for the economic assessment in the LC2B module.

4. ANALYSIS

In this chapter, the data and assumptions used for the analysis and the applied parameter variation are described. Afterwards, the analysis results are presented and discussed.

The following case study is intended to demonstrate that the proposed analysis approach is suitable to assess the overall benefits and costs of the use of PHM and CBM planning in aircraft lifecycle. A focus will be put on the investigation of the operational and economic impact of prognostic errors and the statistical variance of the overall results due to the probabilistic modeling in the aircraft lifecycle simulation. While the results provide no answers regarding the suitability of specific PHM approaches or system architectures, they make it possible to derive technical and economic requirements for those in a subsequent step.

4.1. Data and Assumptions

Studies following the proposed assessment approach require extensive data, which is usually – at least partially – considered confidential by airlines and maintenance, repair & overhaul (MRO) companies. For this reason, the authors have preferably used publicly available information only or have derived the required data under use of assumption from this information.

An aircraft similar to an Airbus A320 will be used as a reference in this study. This applies to the typical aircraft operation, the maintenance program and all recurring and non-recurring costs as well as expected revenues in the operational lifecycle of this type of aircraft. It is assumed that aircraft configurations to be assessed in this study have the same technology level as today's A320 aircraft, but with PHM installed.

The following sections describe the data and assumptions made for the aircraft operation, scheduled and unscheduled maintenance, and relevant operational boundary conditions.

4.1.1. Aircraft Lifecycle and Operations

An operating lifecycle of 25 years is assumed in this study. The aircraft is operated by a full-service network carrier on a short-range rotation with a daily utilization of 8.75 FH. Table 3 shows details of an assumed aircraft operation.

Table 3. Aircraft operational data.

Parameter	Unit	Value
Operating days/week	[d]	7
Night curfew	[h]	7
Flights per day	[FC]	7
FH/FC	-	1.25
Taxi time per FC	[h]	0.3
Turn-around time	[h]	0.75
Block fuel	[kg]	4,000

4.1.2. Aircraft Maintenance and PHM Application

The modeling of unscheduled maintenance events in this study follows the approach as described in section 3.3.2. A total of 25 aircraft subsystems are considered in the study. The failure behavior of each subsystem is described by an individual non-parametric failure distribution function. It is assumed, that 15 of the 25 subsystems are potential candidates for a PHM implementation. The assumed prognostic performance levels are defined in section 4.2

A simplified task-based maintenance program has been modeled as reference maintenance program. It is equivalent to the real A320 maintenance program in terms of man-hours and cost as described in Table 4 (Hölzel et al., 2014). It has been derived from the A320 MPD and more realistic cost data and estimates of the related man-hours published by Aircraft Commerce (2006).

Table 4. Scheduled maintenance program A320 (derived from Aircraft Commerce, 2006).

Check	**Down-time [h]**	**Interval**	**MH [h]**	**Material cost [US$]**
Transit & Pre-flight	0	1 FC	2.6	7
Ramp Check	0	2 d	4	500
Service Check	0	7 d	10	700
A-Check	24	600 FH	80	5.5 k
C-Check	138	18 mo.	2,000	38 k
IL-Check	336	72 mo.	14,300	380 k
D-Check	672	144 mo.	20,000	1.5 M

The maintenance events outlined in Table 4 cover routine and non-routine tasks as well as cabin refurbishments and typical volume of work resulting from Airworthiness Directives (AD) and Service Bulletins (SB).

The modeled reference maintenance program, referred to as equivalence maintenance program in the following, consists of two parts:

1. Task-based (equalized) concept for short and medium interval tasks (former Service Check, A-Check, and C-Check),
2. Block checks for long interval tasks (former IL- and D-Check).

Transit & Pre-flight Checks can be performed at any airport and do not require an additional maintenance downtime. That is why these checks are not considered for the composition of an equivalence maintenance program and in the following maintenance planning and optimization process.

The modeled equivalence maintenance program consists of 12 short interval and 80 medium interval tasks, which represent the maintenance man-hours and task code groups shown in Table 5 over the lifecycle of 25 years. The short interval tasks are characterized by intervals between 80 and 1000 FH. The intervals of the medium interval tasks range from 4,000 to 14,000 FH.

It is assumed that the 6- and 12-year heavy maintenance checks (former IL-/D-check) will persist as block check events. As a consequence, an interval extension of one task of a heavy maintenance check does not lead to an interval escalation of the total check, unless the intervals for all tasks of the checks are being extended accordingly.

Table 5. Equivalence maintenance program – Part 1 (equalized check events).

	TCG	**Short interval**		**Medium interval**	
		MH	Ratio	MH	Ratio
Routine	1	1,898	8.4 %	3,311	11.0 %
	2	2,451	10.9 %	2,350	7.8 %
	3	1,193	5.3 %	2,446	8.2 %
	4	8,798	39.1 %	3,770	12.6 %
Non-routine	5	3,568	15.9 %	8,251	27.5 %
	0	4,597	20.4 %	9,840	32.8 %
	Sum	**22,505**	**100 %**	**29,968**	**100 %**

Analysis of long interval tasks (6-/12-year check tasks and other tasks with intervals longer than generic C-check interval) show that about 89 % account for TCG 1 to 3, which could be subject to task elimination. Only 9 % of the tasks account for TCG 4, which could be subject to interval escalation. The following analysis considers in connection with the block check events only the potential PHM impact of task redundancy, which accounts for almost 90 % of the routine work. The part 2 of the modeled equivalence maintenance program is summarized in Table 6.

Table 6. Equivalence maintenance program – Part 2 (remaining block check events).

	TCG	**IL-Check**		**D-Check**	
		MH	Ratio	MH	Ratio
Routine	1	941		1,568	
	2	1,092	89 %	1,820	89 %
	3	5,963		9,938	
	4	821	9 %	1,368	9 %
	other	183	2 %	305	2 %
	Sum	**9,000**	**100 %**	**15,000**	**100 %**
Non-routine	5	2,500	50 %	4,250	50 %
	0	2,500	50 %	4,250	50 %
	Sum	**5,000**	**100 %**	**8,500**	**100 %**

The applied generic modeling approach allows the comparison of a current maintenance program with any potential or future maintenance program without having described all maintenance tasks precisely. Particularly in early design stages of new aircraft, the proposed methodology could be a viable option to estimate the impact of alternative maintenance concept early on.

4.1.3. Operational Boundary Conditions

A summary of the relevant economic input data used in the analysis is given in Table 7. Assumed ticket prices for economy (EC) and business class (BC) influence airline revenues in the lifecycle CBA.

Table 7. Summary of economic and operational data.

Parameter	**Unit**	**Fiscal year**	**Value**
Ticket price - EC	[US$]	2008	111
Ticket price - BC	[US$]	2008	334
Aircraft price C_0 (incl. 35% discount)	[Mio. US$]	2008	50
Labor rate (maintenance)	[US$/MH]	2009	70
Fuel price (fuel price scenario)	[US$/gal]	2013	2.49
Delay cost	[US$/min/pax]	2009	0.63
Average inflation	[1/year]		0.02
Discount rate *r*	[-]		0.08
Calibration factor revenues	[-]		0.929

The initial investment cost C_0 is assumed as 50 Mio. US$ (aircraft list price in 2008 less an assumed price discount of 35 %). This study does not provide cost estimates for the development and implementation of PHM systems. The goal is to derive maximum acceptable investment costs for PHM systems from the analysis results. Therefore, no additional fix costs for an airplane equipped with PHM are considered. 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 (Eurocontrol, 2007). The internal rate of return *r*, which is used for the discounted cash-flow calculation, is assumed at 8 %. The reference aircraft (see 3.2) has been calibrated with a calibration factor of 0.929 affecting the ticket revenues to an airline internal rate of return of 12 % after 10 years of operation.

4.2. Parameter Variation

The prognostic and CBM concepts to be evaluated in this study are not implemented in commercial aircraft yet. Thus, it is difficult to estimate actual performance characteristics of such concepts on aircraft operational level today. By conducting parameter variations it is possible to analyze the sensitivities of selected parameters with regard to the benefits of an operator's point of view.

The five selected parameters and their values are depicted in Table 8. The parameter p_{UEP} ("unscheduled event prevention") describes the portion of component or subsystem failures for which a specific prognostic system can report imminent failures, without consideration of false alarms and missed failures (see also section 3.4). p_{UEP} can range from 0 to theoretical 100 percent, which means that the respective percentage of the total number of impending failures of the 15 selected subsystems will be predicted. To limit the computing times, the p_{UEP} rates for each of the 15 subsystems are assumed to be identical in all analyses of this study. The parameter p_{FA} ("false alarms") is defined as a probability of occurrence per FH. The "missed failure rate" (p_{MF}) is modeled as a ratio of failure event covered by the PHM system. The "task redundancy" rate (p_{TR}) is the percentage of preventive maintenance tasks that can potentially be eliminated if a PHM system is used to monitor the respective item (see also section 4.1.2). The "interval escalation" rate describes the factor by which preventive maintenance intervals may be extended if the corresponding item is monitored by a PHM system.

Table 8. Parameter space for analysis.

Parameter		**Values**					
p_{UEP}	unscheduled event prevention	0	0.25	0.5	0.75	1	
p_{FA}	false alarms [1/FH]	0	1e-5	5e-5	1e-4	5e-4	
p_{MF}	missed failure rate	0	0.05	0.15	0.25	0.5	
p_{TR}	task redundancy	0	0.2	0.4	0.6	0.8	1
p_{IE}	interval escalation	0	0.25	0.5	0.75	1	

It is important to mention that the parameters p_{UEP} and p_{TR} are modeled independently although an actual PHM system may contribute to both underlying benefits.

The parameter space as defined in Table 8 results in 3,750 separate analyses (for a full factorial experiment), which have been conducted. In this study, each analysis consists of 100 independent simulation runs (Monte Carlo simulations) to account for the stochastic behavior of the unscheduled maintenance module (due to the probabilistic modeling of the component failure behavior and the PHM impacts). The number of Monte Carlo simulations can be understood as a number of simulated aircraft in a fleet, while certain interdependencies within the fleet (e.g. competition of a number of aircraft for limited maintenance capacities) are neglected in this study. Each simulated aircraft comprises an individual failure behavior. The arising variances of analysis results are discussed at the end of section 4.3.

4.3. Analysis Results

The performed analyses provide technical-operational and economic results. All results describe values for the operative lifecycle of a single aircraft. The impacts of PHM on unscheduled maintenance and aircraft operation are shown first. Then, the economic results from an airline perspective are presented. An impression of the variance of the simulated results due to the applied probabilistic modeling approach will be given at the end of this section.

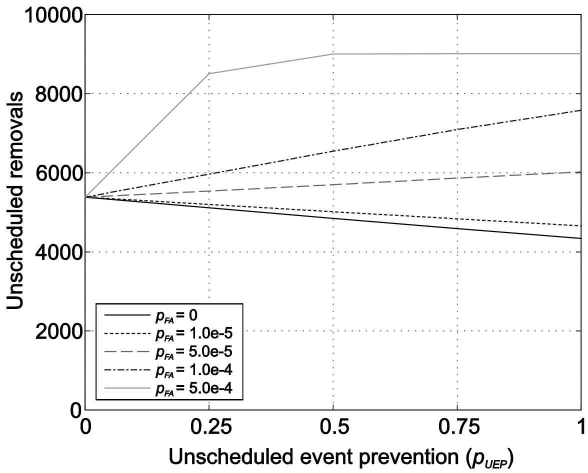


Figure 7. Unscheduled component removals depending on p_{UEP} and p_{FA} (p_{MF} = 0).

Figure 7 depicts the impact of PHM on the number of unscheduled component removals in a/c lifecycle depending on the prognostic performance. In this study, a use of PHM leads to a reduction of unscheduled events from 5,400 to 4,250 in the optimal case (i.e. use of a perfect PHM). Depending on the false alarm rate, the reduction can be smaller or the number of removals can even increase to in case of very values of p_{FA}. The reduction of NFFs leads to a decrease of the number of total events, while false alarms cause additional removals. Possible missed failures have no effect on the number of component removals.

As mentioned before, an unscheduled event results in a technical delay, when a failure (or NFF) is not covered by a PHM system, the MEL is not fulfilled, and MTTR exceeds the available time during a/c turn-around. It can be seen from Figure 8 that the number of technical delays can be reduced by 420 in the best case. But if false alarm rates are very high, the number of delays can increase. Combinations of very high p_{FA} and relatively low prevention rates of unscheduled events (e.g. p_{UEP} = 0.25) seem to be critical. In these cases, an unreliable prognostic algorithm induces a high amount of subsequent failures (and thereby potential delays) not covered by PHM.

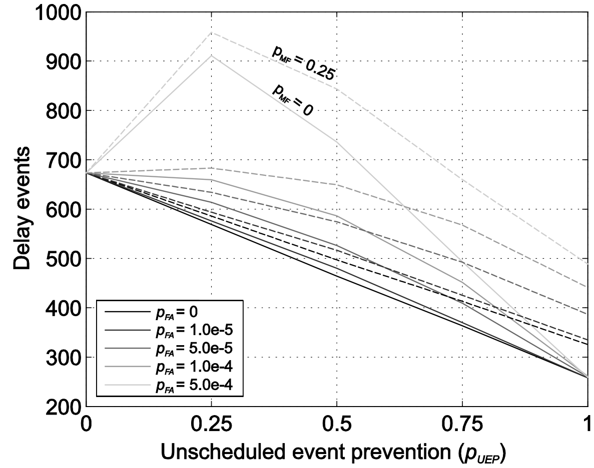


Figure 8. Impact of PHM false alarms and missed failure rate on technical delays (solid line: p_{MF} = 0, dashed line: p_{MF} = 25 %).

As outlines in the beginning, a central goal of a PHM and CBM implementation is to improve the aircraft availability in order to increase the utilization. Both effects, the reduction of unscheduled events and the elimination of redundant tasks, can contribute to higher aircraft utilization. Figure 10 shows that – even without a change in the aircraft operation concept – up to 675 additional flight cycles could be realized in aircraft lifecycle.

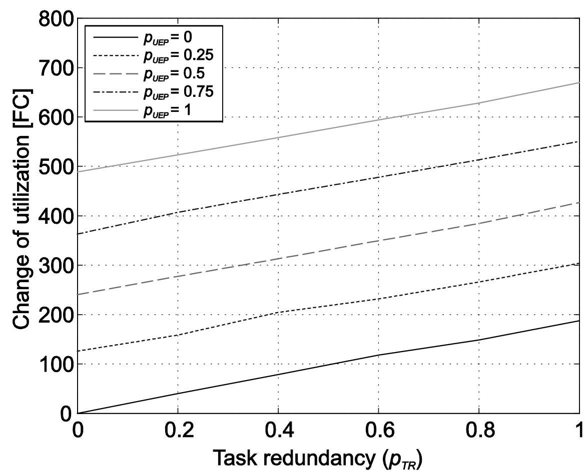


Figure 9. Impact of task redundancy (p_{TR}) and unscheduled event prevention (p_{UEP}) on aircraft utilization.

Under the assumptions of this study, the avoidance of unscheduled events enables up to 485 additional flight cycles. Another 190 flights can be realized by shortening the maintenance downtimes for IL- and D-Checks in case of p_{TR} = 1. This picture changes in the case of high false alarm rates as shown in Figure 10.

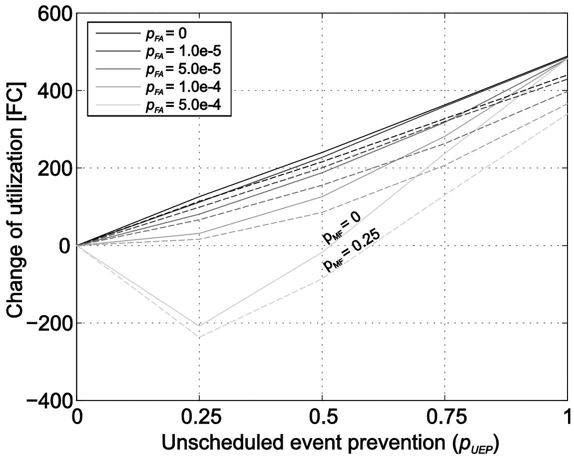


Figure 10. Impact of PHM false alarms and missed failure rate on aircraft utilization for p_{TR} = 0 (solid line: p_{MF} = 0, dashed line: p_{MF} = 25%).

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. Figure 11 shows the potential reduction of DMC/FH for a varying p_{TR} and different p_{UEP}.

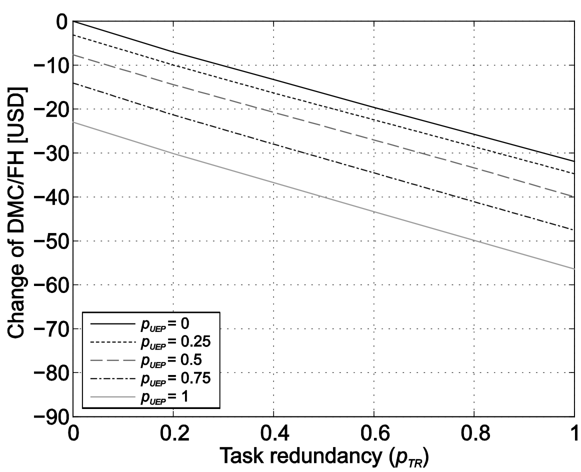


Figure 11. Impact of task redundancy (p_{TR}) and unscheduled event prevention (p_{UEP}) on of DMC per FH (for p_{IE} = 0).

The introduction of a CBM concept has influences on the amount of maintenance man-hours performed on a planned basis. Figure 12 and Figure 13 show the impacts of a variation of the parameters p_{TR} and p_{IE} on man-hours for equalized maintenance events (planned in AIRMAP). The absolute level of man-hours at p_{Cov} = 1 (Figure 13) is about 17,000 hours higher (over the lifecycle) than at p_{Cov} = 0 (Figure 12). The component removal events covered by PHM are responsible for this different level of man-hours. The shape of the curves is identical in both cases. In the reference case (without PHM), this workload has to be carried out instead on a reactive basis.

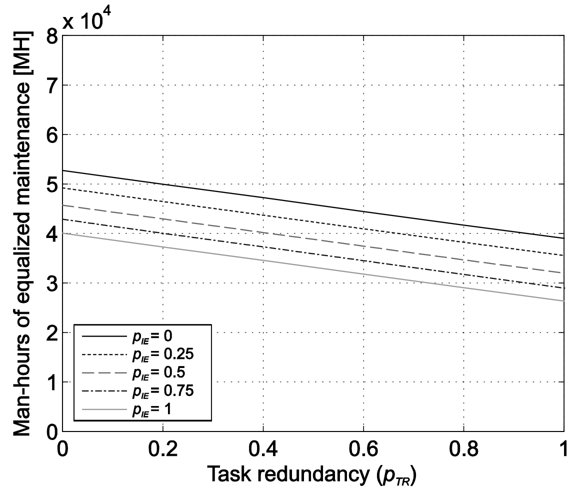


Figure 12. Man-hours of equalized maintenance events (p_{UEP} = 0).

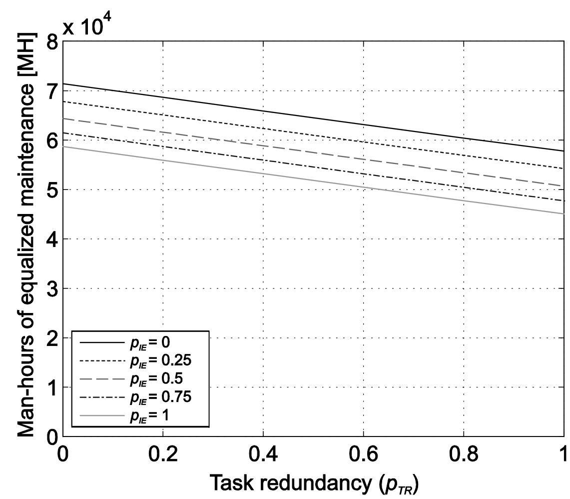


Figure 13. Man-hours of equalized maintenance events (p_{Cov} = 1).

The following figures describe the highest aggregated economic results of the presented study. The monetary benefit of an aircraft operator, expressed as NPV, is shown for different variations and combinations of the five selected parameters.

Figure 14 presents the impacts of p_{UEP} on NPV for different p_{MF} in combination with p_{TR} = 0 and p_{TR} = 1. The range of NPV improvements can vary by around 3 million US$ in this case. An extremely unreliable prognostic system that produces high numbers of false alarms can cause tremendous extra maintenance costs and reduced aircraft utilization with corresponding decreases of the operator NPV (Figure 15).

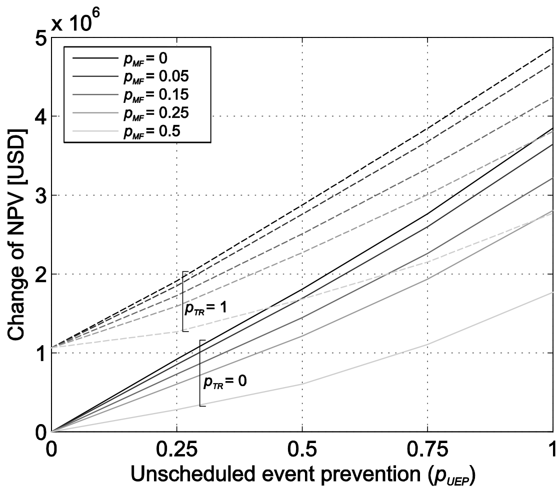


Figure 14. Impact of unscheduled event prevention (p_{UEP}) and missed failures on NPV (solid line: p_{TR} = 0, dashed line: p_{TR} = 1).

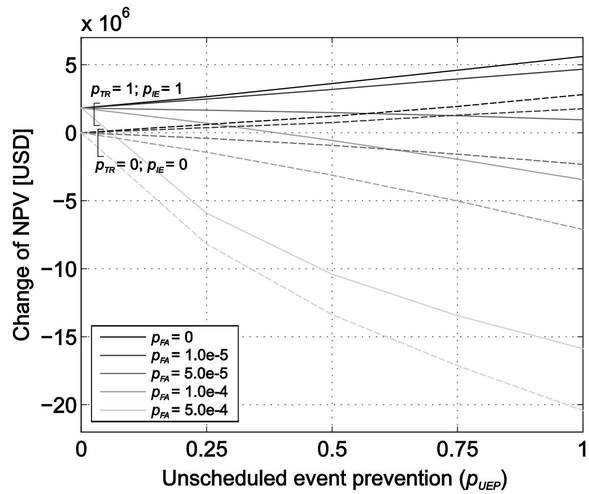
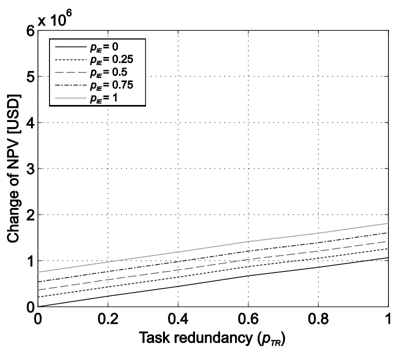
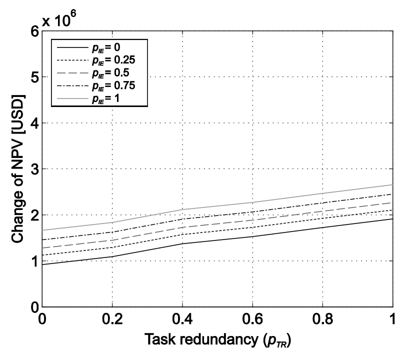


Figure 15. Impact of unscheduled event prevention (p_{UEP}) and prognostic missed failures on NPV (solid line: p_{TR} = 0 and p_{IE} = 0, dashed line: p_{TR} = 1 and p_{IE} = 1).

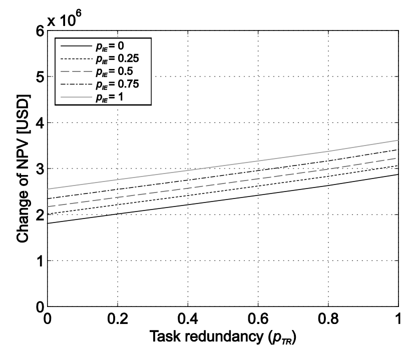
The simulated results for all variations of p_{UEP}, p_{TR}, and p_{IE} are shown in Figure 16. Each of the five parts of the figure shows the impacts of the task redundancy rate and the interval escalation factor on airline NPV with the respective PHM coverage rate. It can be seen that the maximum benefit of an interval escalation (i.e. the difference of NPV for p_{IE} =0 % and p_{IE} =100 % in each subfigure) accounts for around 0.85 million US$. The maximum overall increase of NPV that could be realized under given assumptions is 5.6 million US$ (as depicted in Figure 16 e). Although it is highly unlikely that a PHM-coverage of 100 % for the selected systems could be achieved at an acceptable price, the results show the range of potential benefits. The increase in NPV by a certain PHM/CBM configuration is at the same time the upper limit of the acquisition cost of such a system,



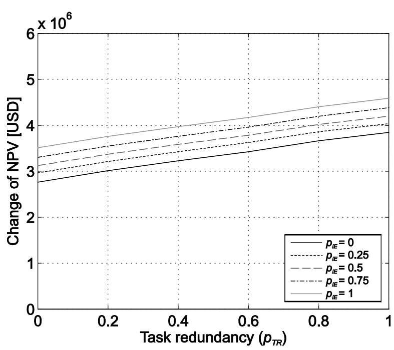
a) p_{UEP} = 0



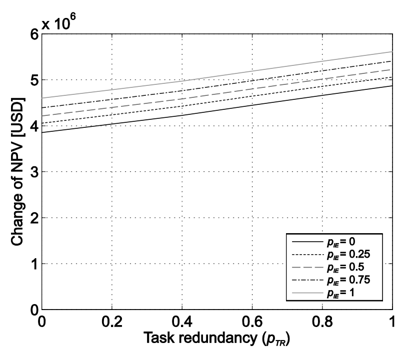
b) p_{UEP} = 0.25



c) p_{UEP} = 0.5



d) p_{UEP} = 0.75



e) p_{UEP} = 1

Figure 16. Impact of unscheduled event prevention (p_{UEP}), task redundancy (p_{TR}), and interval escalation rates (p_{IE}) on NPV.

which could be accepted.

Since each of the analysis results is a mean value of 100 simulations the values may be subject to significant variances. A graphic evaluation of the variance of the simulation results indicates a relatively high selectivity of the individual analyses. This means e.g. that a PHM system with $p_{UEP} = 0.5$ very likely leads to less component removals than a system with $p_{UEP} = 0.25$ even in a realistic operational scenario. The distributions of the number of component removals – as depicted in Figure 17 – show small overlaps between the different values for p_{UEP}.

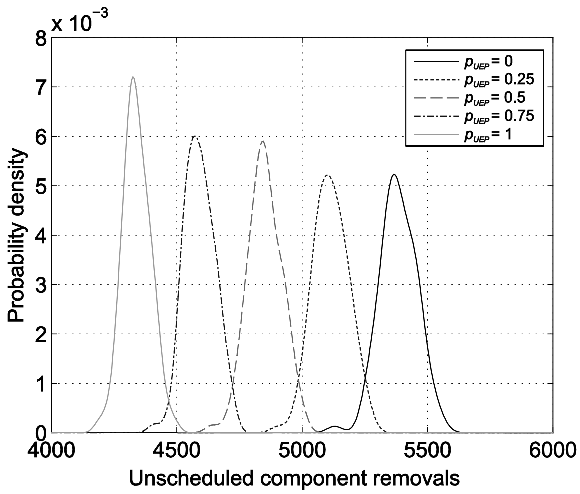


Figure 17. Variation of simulated unscheduled component removals for different PHM coverage rates.

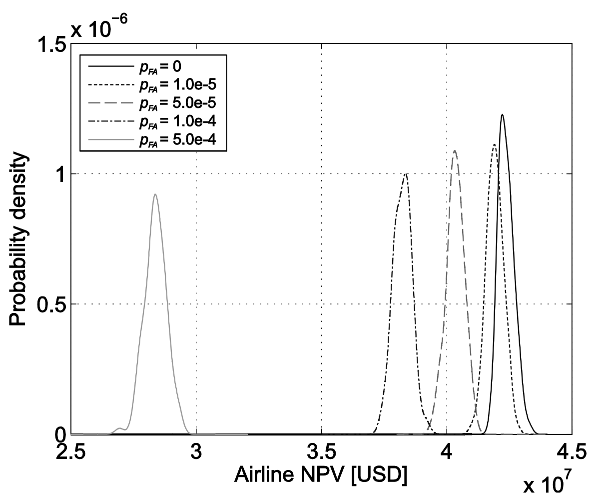


Figure 18. Variation of simulated airline NPVs for different prognostic false alarm rates (for $p_{UEP} = 0.5$).

Figure 18 shows again relatively small variances of the simulated results. But a significant overlapping of the results exists for the perfect PHM and the smallest false alarm rate. That means it cannot be guaranteed that an aircraft equipped with the (theoretical) perfect PHM will perform better over the lifecycle than a system with a small false alarm rate. A considerable overlapping of the results can be observed also for the simulated NPV values depending on different p_{UEP} as shown in Figure 19.

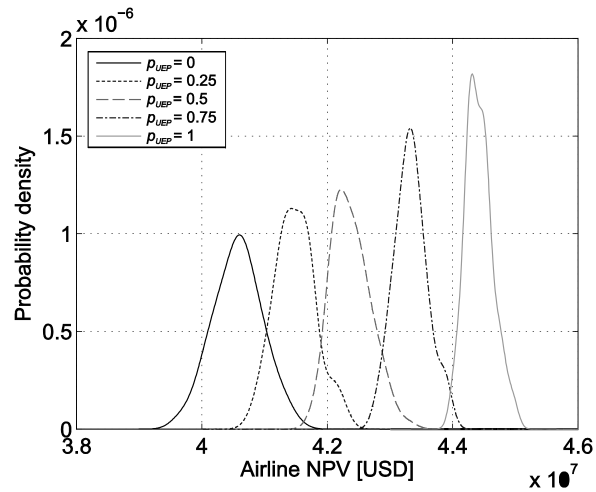


Figure 19. Variation of simulated airline NPVs for different PHM coverages (perfect PHM).

It becomes clear that due to the many stochastic factors acting here (and in reality), a considerable uncertainty exists with regard to the value of a PHM use that can be expected in a real-world aircraft operation.

5. CONCLUSION AND OUTLOOK

In this paper we have presented an integrated approach to model the impacts of PHM and CBM planning from an aircraft lifecycle perspective considering prognostic performance levels and errors. The integration of the CBM planning approach in a lifecycle cost-benefit model allows the economic assessment of a PHM and CBM implementation in future aircraft. The application of the assessment approach can deliver valuable requirements for the future development of PHM and CBM concepts and demonstrate its consequences for operators and MROs.

The analysis results show that benefits by a PHM implementation can only be expected, if a very detailed examination is made. Especially high false alarm rates have the potential to cause an economic deterioration compared to the reference system.

Since the general assessment approach is generic in nature, it can be adapted to all kinds of technologies and types of aircraft. For the analysis of a different aircraft type, AIRTOBS must be configured with the aircraft and operator specific XML-file. Furthermore, the corresponding maintenance program and the failure behavior of the systems under consideration must be provided.

At present, the assessment approach is limited to a single aircraft analysis. An extension of AIRTOBS on a fleet-level is in preparation to allow full use of the maintenance planning and optimization approach implemented in AIRMAP, i.e. scheduling maintenance tasks and planning capacities for a fleet of different aircraft types on an airline's network. While currently one aircraft lifecycle is simulated at the time, an analysis on fleet level requires the simultaneous simulation of multiple aircraft in order to capture the interdependencies within the fleet. An analysis on a fleet-level allows an even more realistic assessment of PHM, while it is expected that this will result into a lower economic benefits per aircraft. This is because several aircraft compete for limited maintenance resources, leading to less efficient solutions of the CBM planning process.

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NOMENCLATURE

AIRTOBS	Aircraft Technology and Operations Benchmark System
CBA	cost-benefit analysis
CBM	condition-based maintenance
DMC	direct maintenance cost
DOC	direct operating cost
FC	flight cycle
FH	flight hour
LCC	life cycle cost
LRU	line replaceable unit
MEL	minimum equipment list
MH	man-hours
MPD	maintenance planning document
MRO	maintenance, repair, and overhaul
MTTR	mean time to repair
NFF	no fault found
NPV	net present value
PDF	probability density function
PHM	Prognostics and Health Management
ROI	return on investment
RUL	remaining useful life
XML	Extensible Markup Language

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Volker Gollnick holds the chair and directorate of the Institute for Air Transportation Systems of the German Aerospace Center (DLR) at the Hamburg University of Technology (TUHH). He holds a Diploma degree in Mechanical and Aerospace Engineering from the Technical University of Braunschweig and a Ph.D. degree from the Technical University of Munich. In his research he is in particular interested in operational improvements and changes of sustainable but efficient air transportation systems. Integration and collaboration of the various stakeholders is his special focus, when he is researching on new aircraft, airports and aircraft operations. He represents more than 20 years of experience in aerospace industry and government. He held responsible roles in particular in flight testing, overall aircraft design, cockpit and avionics systems at EADS and its subsidiaries and the German Forces Flight Test Center.