A Maintenance Packaging and Scheduling Optimization Method for Future Aircraft

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This paper proposes an optimization method for aircraft maintenance tasks packaging and scheduling integrated in an aircraft lifecycle simulation. It is demonstrated that the developed methods are feasible to model a prognosis-based maintenance concept. Such maintenance concepts are a prerequisite for a profitable application of prognostics and health management systems in future aircraft. The applicability of the method is analyzed and economically assessed over an aircraft lifecycle considering aircraft operation. The analysis shows that a variation of the maintenance opportunities frequency for a short-range aircraft, provided in the aircraft rotation plan, can have a significant influence on the operator's net present value (NPV). A benefit of up to 2.8 million USD, representing 1.2% of the operator's NPV, can be realized, when maintenance opportunities are provided every 3 instead of every 7 days, while aircraft utilization is assumed to be constant. Compared to a traditional block check concept the presented method leads to higher maintenance costs, under the condition that the same volume of maintenance work has to be carried out.

Nomenclature

AIRMAP	=	Aircraft Maintenance Planning
AirTOBS	=	Aircraft Technology and Operations Benchmark System
C	=	cost [USD]
C_0	=	initial investment [USD]
C_i	=	cash flow in the *i*-th year [USD]
DMC	=	direct maintenance cost [USD]
DOC	=	direct operating cost [USD]
FC	=	flight cycle
FH	=	flight hour
FSB	=	flight schedule builder
LC2B	=	life cycle cost-benefit model
LCC	=	life cycle cost [USD]
LRU	=	line replaceable unit
MH	=	man-hour
MEL	=	minimum equipment list
MRO	=	maintenance, repair, and overhaul
MSB	=	maintenance schedule builder
MTBUR	=	mean time between unscheduled removals [FH]
MTTR	=	mean time to repair [h]
NPV	=	net present value [USD]
PHM	=	prognostics and health management
r	=	required rate of return
RUL	=	remaining useful life [FH]
t	=	time

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I. Introduction

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. Therefore aircraft manufacturers are aiming for a drastic reduction of the scheduled maintenance programs for future aircraft. In the ideal case – even though it will probably never be reached – there will be no more scheduled maintenance programs. This means a complete shift away from a preventive to a condition- or prognosis-based maintenance strategy. It enables an optimal utilization of the remaining useful lifetimes of aircraft components and (in theory) the minimization of ground times and maintenance events.

Technical and organizational requirements must be met in order to achieve a widely prognosis-based maintenance. The aircraft must be equipped with diagnostic and prognostic systems, which are able to monitor the state of health of components and systems, and to announce impending failures in time. Prognostics and Health Management (PHM) systems may help to reduce both, operational interruptions due to unscheduled maintenance events, and maintenance downtimes due to (unnecessary) preventive maintenance.[1] Industrial an academic research is working on PHM systems for many years and has announced significant advances. But several challenges have still to be resolved for the onboard deployment of an aircraft-wide system.[2]

A. Future maintenance concepts and technologies

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. In many cases safety critical items have hard times today. If a PHM system can ensure a reliable detection of an imminent fault of this item, its useful lifetime can extend substantially.

Unscheduled maintenance events and no-fault-founds (NFF) can be prevented, when an efficient PHM system reports imminent failures and localizes failure root-causes. The mentioned effects can lead to significant reductions in maintenance downtime and costs.[3]

Individual loads and production tolerances lead to different component degeneration, which finally results in an individual remaining useful life (RUL) of component or a system. PHM technology is able to estimate the RUL of an item based on the individual state 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.[4]

A single-task-oriented and condition-based maintenance concept is required, when aiming for high utilizations of component's RULs. In the following we call such a concept a prognosis-based maintenance. On the organizational side, a fully prognosis-based maintenance leads to great challenges. Today´s maintenance programs are characterized by preventive and corrective tasks. While preventive tasks with fixed intervals are foreseeable and easy to plan, time and effort for corrective work is more difficult to plan as they arise from the results of (preventive) inspections. A wider use of prognostics can lower the portion of preventive tasks and thereby reduce the predictability of future maintenance work. With prognostics, many preventive inspections may become obsolete, while prognosis-based tasks have to be planned and carried out with (potentially) short warning times. Predicted RULs are not fixed but deviate depending on further component degradation trends. This leads to the necessity of more flexible maintenance planning processes in order to support prognostic systems in an optimal way. Maintenance activities have to be grouped together ("packaging") and performed at the right point in time ("scheduling") depending on estimated remaining useful life (RUL).[5] It is be the goal to minimize aircraft maintenance downtime and costs while aircraft rotation planning and limited maintenance capacities are considered.

II. Methodology

The approach presented in this paper is based on a branch-and-bound algorithm for maintenance planning and a discrete-event simulation of aircraft operation. The results are evaluated with a life cycle cost-benefit analysis. An overall architecture containing these models has been established for the intended analysis.

A. 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.[6,7] 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, the lifecycle cost-benefit model AirTOBS (Aircraft Technology and Operations Benchmark System) was developed.

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, 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.

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. 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.

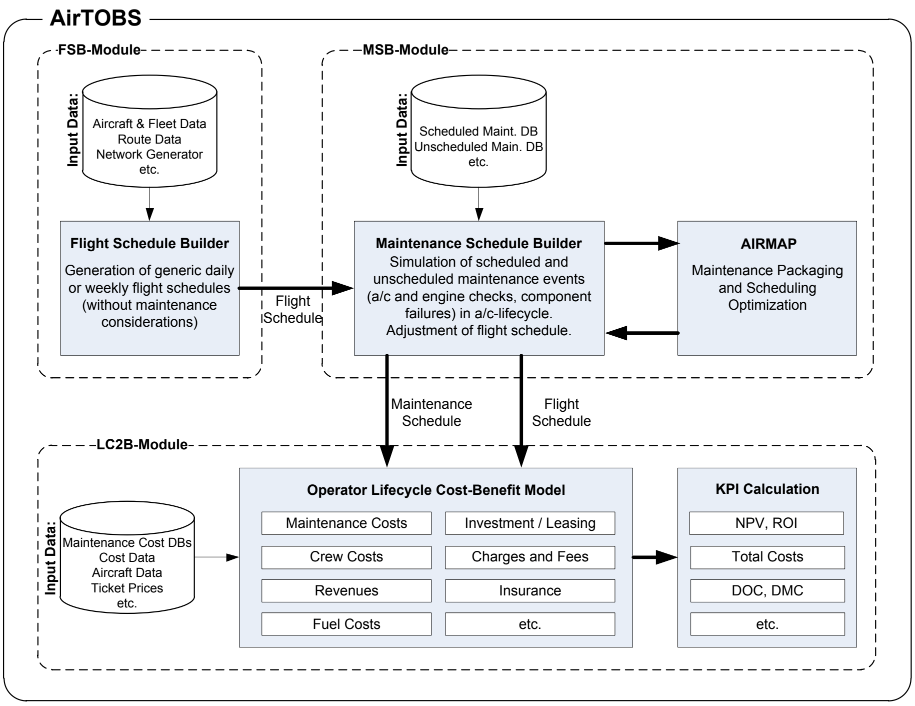

Figure 1: Overview of aircraft lifecycle cost-benefit model with integrated Maintenance Packaging and Scheduling Optimizer

To analyze new maintenance concepts, like a prognosis-based maintenance in combination with PHM-use in this study, the Aircraft Maintenance Planning (AIRMAP) Optimizer module can be linked to the MSB. AIRMAP produces an optimized maintenance schedule based on intermediate results from the MSB. The methodology used in AIRMAP is described in section B.

After the optimized 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 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. All values are escalated over the aircraft lifecycle to account for inflation, before they can be summarized as net present value (NPV). The NPV is a common metric to quantify a project's net-contribution to wealth[8] for a certain period of time, while accounting for the time value of money and the opportunity cost of capital. 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.

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

Unscheduled maintenance is considered on an accumulated ATA-Chapter level or by a provided component database. Using the modeled lifetime flight schedule, unscheduled events can be simulated based on mean times between unscheduled removals (MTBUR) or component failure distribution functions, aircraft related mean times to repair (MTTR), e.g. time needed for a component or line replaceable unit (LRU) replacement. Component failures 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.

The weekly availability is based on seven 24 hour days and is reduced by night curfews at airports. The resulting availability is further reduced by taking the flight schedule into account, including turnaround and block times. From this flight schedule line maintenance events are derived, assuming no influence on the flight schedule while accounting for cost.

To consider the influences of maintenance strategies and component reliabilities on spare part 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.[9]

B. Maintenance Planning Optimizer

The planning of aircraft maintenance is the allocation of maintenance tasks (i.e. objects) to be performed on specific aircrafts 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[10,11]. 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[*]. NP-hard problems can be solved heuristically in polynomial time with branch-and-bound algorithms.[12]

The algorithm described below, as used in AIRMAP, is able to solve the previously formulated NP-hard AIRMAP-Model[13] in polynomial time. The AIRMAP-Optimizer can be characterized as a depth-first-search branch-and-bound algorithm.

As specified in section I, aircraft operators and manufacturers strive to shift away from a scheduled (i.e. hard-time) to a prognosis-based maintenance. Prognosis-based tasks have to be planned and scheduled in a way that leads to an economic optimum.

The optimizer can function as a planning interface between flight and ground operations of future aircraft equipped with PHM-technology. It uses data inputs from flight and maintenance operations as shown in Fig. 2. Based on the aircraft rotation defined by flight operations and considering restrictions of the maintenance organization (capacities and capabilities), the optimizer creates a maintenance schedule at minimized total costs. This maintenance planning process can be executed for a single aircraft or an entire fleet of aircraft with different aircraft types for any finite planning horizon.

The optimizer follows a single-task-oriented approach. Each ground time of an aircraft (turnaround times and overnight stays) is regarded as a maintenance opportunity. The goal is to avoid additional maintenance downtimes and to utilize existing maintenance opportunities efficiently. This can be done by appropriate clustering of maintenance tasks, while considering technical (maintenance intervals or RULs reported by a PHM-system) and organizational restrictions.

[*] NP-hard (non-deterministic polynomial-time hard) problems cannot be efficiently solved in polynomial time. By using adequate heuristic algorithms it is possible to efficiently verify integer optimization problems.

The RUL estimate is a major input parameter for AIRMAP. The duration of maintenance tasks and costs can be derived from maintenance documents in combination with MRO's experience. The aircraft rotation plan provides the optimizer with the aircraft location at a specific time, the aircraft type, and the tail sign.

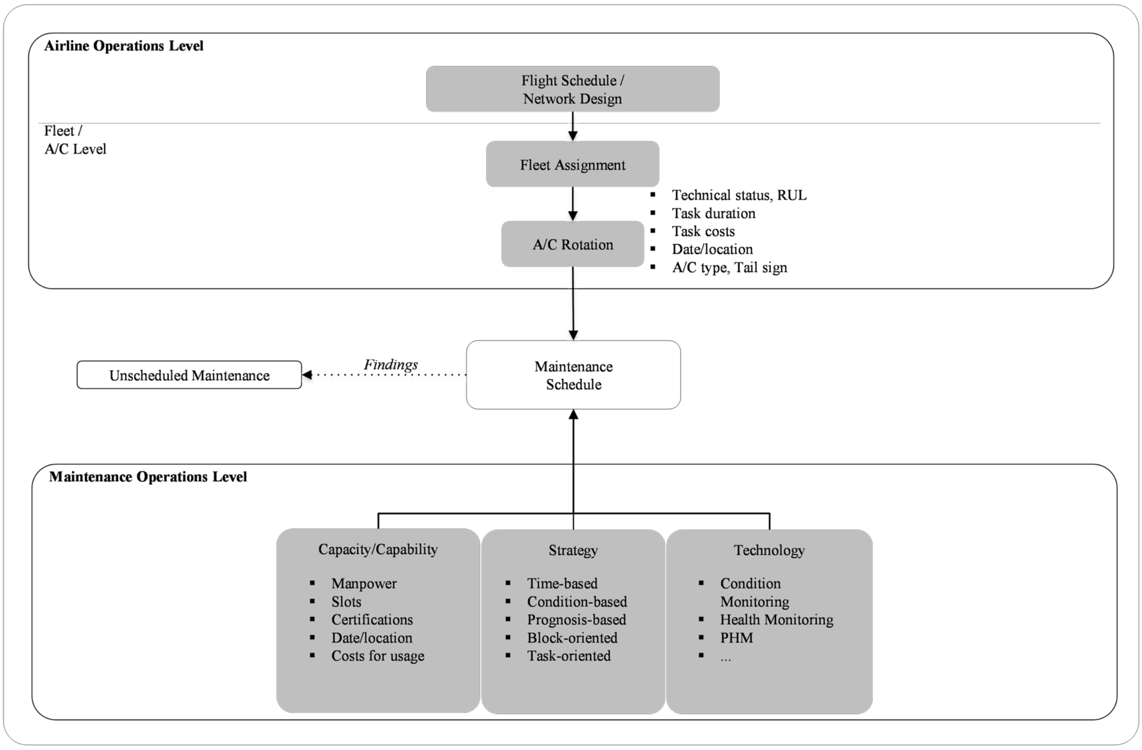

Figure 2: Airline Optimization Model

The main variables and restrictions regarding maintenance operations are those in the block 'Capacity/Capability' in Fig. 2. A maintenance schedule is valid, if

- the available manpower is sufficient to execute the allocated tasks,
- enough free maintenance slots are available (e.g. for tasks to be performed in hangar environment),
- required certifications for the aircraft type are available at specific maintenance location,
- and the aircraft ground time is sufficient to execute the allocated tasks at the selected maintenance location.

The optimizer charges costs for usage of a maintenance opportunity in order to minimize additional fix costs that can be expected for a maintenance event.

Optimizer program flow

In Fig. 3 the optimizer program flow is shown. After read-in of relevant input data (1.) from airline (*Tasks*) and maintenance operations (*Opps*), the algorithm is configured with the following parameters (2.):

1. *Usage factor* (from 0 to 1) – regulates the minimum share of the RUL that must be used before a maintenance task may performed.
2. *iMax* – determines the number of iterations.
3. *1st Bound* – feeds the branch-and-bound algorithm with a first reference, which must be a great value (e.g. 10^{10}).

In the first branch (3.) the optimizer tries to find at least one proper opportunity for each task. In case of one or more unallocated tasks, the algorithm stops, because no valid maintenance schedule can be created. The user can see from the output values, which tasks have not been allocated due to a lack of maintenance capacities.

When sufficient maintenance opportunities exist, the complete list of tasks to be performed is sorted in the next step (4.). Both, allocating the task with the highest priority first (i.e. the one with the smallest RUL) or allocating the task with the highest cost can be reasonable. However, our tests have shown that better results can be achieved when sorting the tasks by cost in descending order. Since the optimizer considers costs for waste of life, it is beneficial when the most expensive task (with potentially high costs for waste of life) can be allocated to a maintenance opportunity short before the predicted failure occurs. The wasted life variable is calculated for each task for all proper maintenance opportunities with Eq. (2). When new problems or optimizations with changed parameters should be solved, it is recommended to test both sorting methods in order to reach the best results. The sorting process represents the branching strategy.

$$Cost\ of\ wasted\ life = \frac{Lifetime - RUL\ at\ maintenance\ date}{Lifetime} \cdot Task\ Cost \tag{2}$$

In the next step, the first task in the list is selected and a proper opportunity is searched (5.). If there is no remaining match, the current iteration quits and the optimizer tries to find another maintenance schedule. If there is a match with several maintenance opportunities, the cheapest one is selected. This whole loop is repeated until each task is allocated to its cheapest maintenance opportunity (6.). When all tasks have been allocated, the total costs of the current plan are calculated (7.). A new best plan is found, if the total costs are below the costs of the previously found best plan. This procedure is repeated as long as the iteration limit *iMax* is not reached. The final result of the optimizer is the maintenance schedule with the lowest overall costs, which could be found.

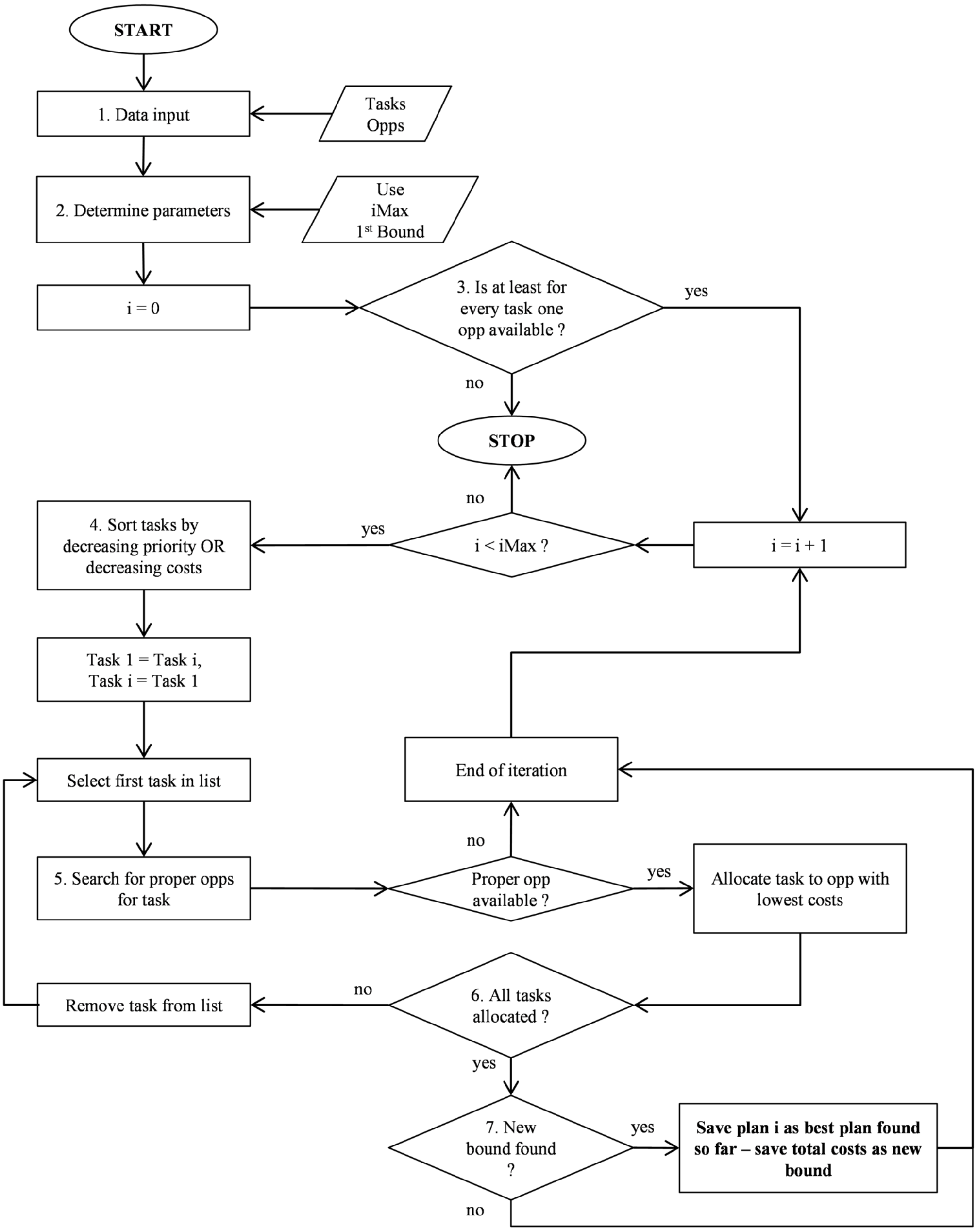

Figure 3: AIRMAP-Optimizer program flow

Optimizer characteristics

In general, the optimizer prefers late maintenance opportunities in order to minimize the waste of life. Nevertheless, earlier maintenance resulting in higher waste of life can lead to lower overall costs. This is the case, when fixed costs of an additional maintenance event including loss of production costs are higher than the waste of life cost. By modification of the input variables RUL, task duration and task costs the influence on maintenance packaging, scheduling and costs can be evaluated. Controlling these three variables it is possible to simulate alternative aircraft maintenance strategies with tasks resulting from different health managing technologies applied to an aircraft.

C. Integration of AIRMAP-Optimizer in AirTOBS-Model

The lifecycle cost-benefit analysis of the prognosis-based maintenance concept in AirTOBS is limited to a single aircraft. Therefore the following calculations in AIRMAP are limited on a single aircraft either, although the optimizer is able to handle a fleet of aircraft.

For a global analysis of the impact of a prognosis-based maintenance concept on aircraft operator's NPV it is necessary to integrate the AIRMAP model into AirTOBS and to establish appropriate data interfaces (Fig. 4).

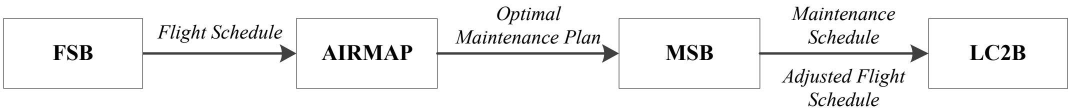

Figure 4: Model integration and interface definition

Based on the flight schedule prepared by the FSB a maintenance opportunities table for a two month long planning period is produced by AIRMAP. The optimizer allocates the maintenance tasks to the opportunities in the current planning period. Tasks with due-dates outside the current period are shifted to the next period. After completion of all planning periods in the aircraft lifecycle the resulting maintenance plan is transferred to the MSB. Then all events included in the maintenance plan are integrated into the aircraft lifecycle simulation. Finally, the resulting maintenance and flight schedule is delivered to the LC2B, where the airline's cash flows are calculated.

III. Analysis and Results

A simulation of a 150-seat short-range aircraft, followed by a lifecycle cost-benefit analysis will show the potential advantages of a prognosis-based maintenance concept. Furthermore it will provide information on economical, technical, and organizational requirements to be met for a future implementation of the concept.

A. Input data and assumptions

Since data availability for future aircraft is extremely limited, we selected an Airbus A320 type of aircraft for demonstrating the maintenance optimization approach together with the assessment framework. An operating lifecycle of 25 years is assumed.

The aircraft's maintenance program is based on today's scheduled maintenance programs as shown in Table 1. The aircraft in this study is equipped with a PHM system, which allows performing former preventive maintenance tasks on a prognosis basis. Unscheduled maintenance events and its consequences like flight delays or cancellations are neglected in this paper. A list of tasks to be allocated by the maintenance optimizer has been derived from the mentioned scheduled maintenance program. Only maintenance man-hours from Weekly, A-, and C-Checks have been extracted as AIRMAP-input. The selected block-checks have been split up into small work packages of 4 to 9 hours which can be handled during regular aircraft ground times. Costs have been equally distributed over the work packages.

Table 1: Scheduled maintenance data of A320-family aircraft[14]

Name	Downtime *[h]*	Intervals				Man-hours	Material cost *[USD]*
		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

In this paper we assume that heavy maintenance checks (former IL- and D-Check) will still be necessary for future aircraft, because many detailed inspections and overhaul actions cannot be divided into smaller work packages. Although a reduction of heavy maintenance expenditure through the use of new materials (e.g. CFRP) can be expected, it is assumed as unchanged in the following analysis.

The aircraft operation follows a typical aircraft rotation on short-range with a network carrier resulting in a daily utilization of 7.5 flight hours and a total daily cycle time (i.e. sum of flight hours, taxi-times, and turn-around-times) of 13.8 hours. The remaining 10.2 hours per day function as a maintenance opportunity, when the aircraft is located at a maintenance station.

B. Analysis

A flight schedule with daily utilizations, maintenance opportunities (including frequencies, ground times, and available manpower) and event cost have been defined for four different scenarios as shown in Table 2.

Table 2: Aircraft operation and maintenance opportunities

		Baseline	Low	Medium	High
Daily utilization		7.5 FH / 13.8 CH	7.5 FH / 13.8 CH	7.5 FH / 13.8 CH	7.5 FH / 13.8 CH
Maintenance opportunities	*Frequency*	Block check program	Every 7 days (6 in 2 month)	Every 5 days (9 in 2 month)	Every 3 days (20 in 2 month)
	Ground time		10.2 h	10.2h	10.2 h
	Manpower		20	20	20
Fixed maintenance event cost		-	2,000 USD	2,000 USD	2,000 USD

The 'Baseline' scenario acts as the reference of today's maintenance programs, while the three remaining vary in their frequency of maintenance opportunities. The aircraft rotation in the "Low" scenario provides a maintenance opportunity every seven days, in case of the "Medium" and "High" scenario every 5 and 3 days respectively. More infrequent opportunities preclude the finding of feasible maintenance plans while more frequent opportunities allow better solutions but more stringent constraints for the aircraft rotation planning process. The length of the ground-time and the number of available mechanics ("*Manpower"*) is assumed to be equal for all scenarios. In addition to the variable maintenance event costs, an additional fixed cost rate ("*Fixed maintenance event cost*") of USD 2,000 will be charged for the use of a maintenance opportunity.

C. Results

The analysis results reflect the characteristics of the AIRMAP optimizer described in section B. It can be seen from Fig. 5 that the optimizer uses more maintenance opportunities, when more opportunities are available. An extension of opportunities functions as a relaxation of constraints in the optimization problem and consequently enables better solution.

Figure 6 shows the delta NPV curves of three scenarios with "Low-frequency opportunities" as reference. The provision of more maintenance opportunities lead to an increased NPV of 2.1 million USD (0.9%) in case of scenario "Medium" and 2.8 million USD (1.2%) in case of scenario "High" compared to the scenario "Low".

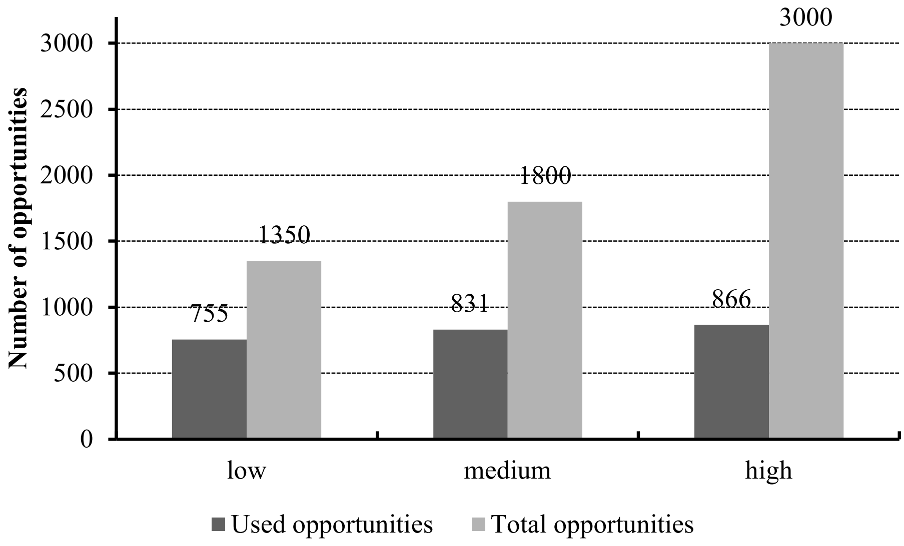

Figure 5: Opportunities used for maintenance

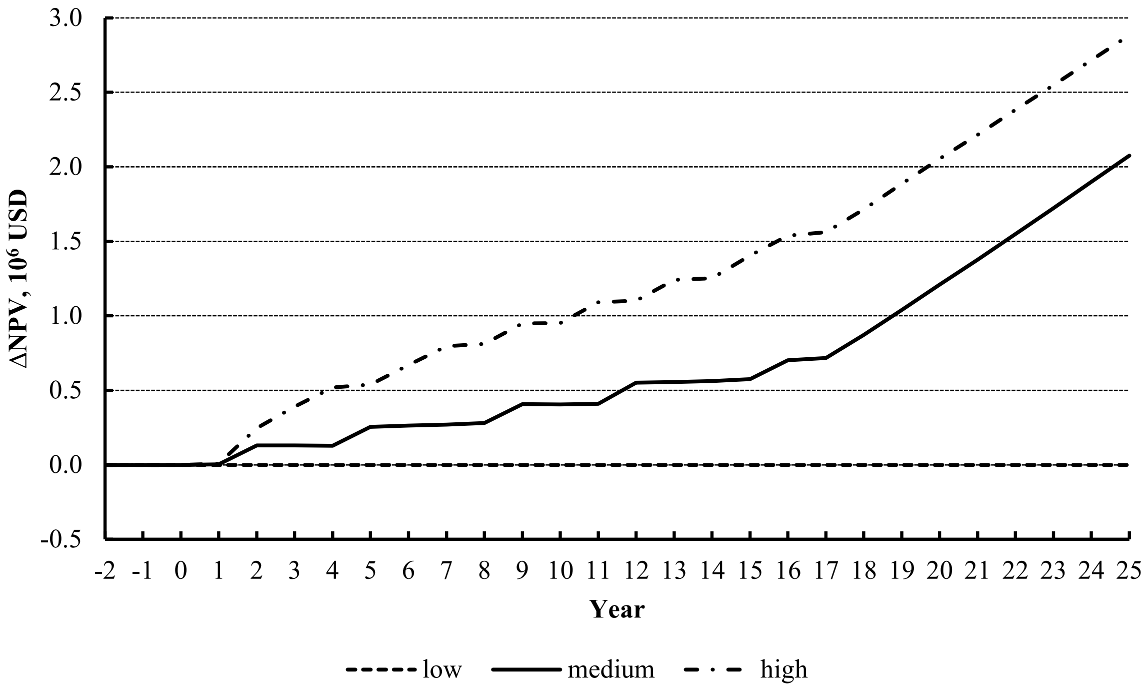

Figure 6: Delta NPV curves for maintenance opportunity scenarios

When comparing the "Medium" scenario with the "Baseline" (Fig. 8), it becomes obvious that the NPV of "Medium" at the end of operating life is significantly lower than the NPV of the reference. All three AIRMAP scenarios produce an economic result that is between 7.7 and 10.6 million USD lower than the reference. This fact is surprising because the reduced maintenance downtimes resulting from the breakup of A- and C-Checks should lead to increasing aircraft utilizations and ticket revenues. The reason is located in the maintenance packaging and scheduling which seems to deliver results that are inefficient compared to a traditional block check concept. Repeated selections of earlier than necessary maintenance opportunities lead to large increases in maintenance cost, when the waste of life results in additional maintenance events over the lifecycle.

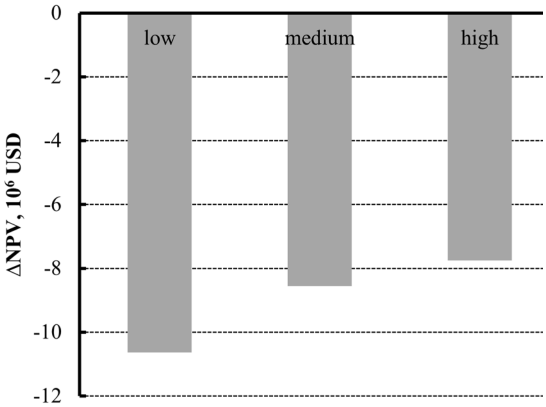

Figure 7: NPV of the three scenarios compared to reference

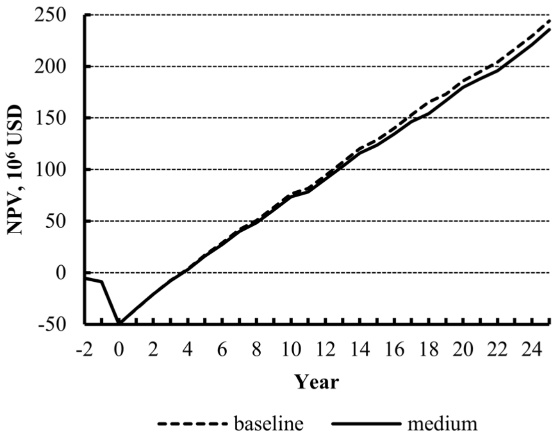

Figure 8: Comparison of 'Baseline' and 'Medium' scenario

We expect that significant improvements in efficiency are possible with further studies of the optimal parameter settings in AIRMAP. It is the goal of this study to focus on the effects of a prognosis-based maintenance concept without mixing it up with the benefits of a PHM technology. When the extension of useful life of components and the omission of many inspections due to the implementation of PHM are included in an analysis, the prognosis-based maintenance concept might be very beneficial. Detailed data of resulting useful lifetimes and of maintenance tasks – while considering the reliability of the PHM systems – are required to provide a profound assessment in future studies.

IV. Conclusion

In this paper we have presented an approach to model a prognosis-based maintenance concept for future aircraft and to analyze its economic impact on a lifecycle level. The study indicates that the method chosen in AIRMAP is feasible to conduct the maintenance scheduling and packaging process for future aircraft. Improvements are necessary to achieve a sufficient efficiency in the lifecycle. Therefore more detailed analysis of optimization results and adjustments of optimizer parameters are planned.

The integration of AIRMAP and AirTOBS allows the economic assessment of maintenance concepts on a lifecycle level. It can deliver valuable requirements for the future development of condition- and prognosis-based maintenance concepts and its consequences for operators and MROs. The consideration of extended and varying lifetimes through the use of PHM would be reasonable for comprehensive comparisons to current maintenance concepts.

An extension of AirTOBS on a fleet-level basis would allow using the complete functional range of AIRMAP – scheduling maintenance tasks and planning capacities for a fleet of different aircraft types on an airline's network. In further studies we intend to analyze the effects of varying daily aircraft utilizations in order to investigate the applicability of the approach for different airline business models (e.g. network or low-cost carrier).

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