Aircraft Lifecycle Cost-Benefit Analysis of PHM Systems

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The use of prognostics and health management (PHM) systems can improve operational reliability by reducing delays and cancellations caused by unscheduled maintenance events and no-fault-founds (NFFs). While PHM systems have no influence on components' failure distributions, they can improve the operational reliability of an aircraft. This is achieved by performing maintenance tasks prior a component failure based on the remaining useful life (RUL) predicted by the PHM system and by reducing NFFs based on health monitoring information of the PHM system. This study presents an analysis of the monetary potential of an improved operational reliability and reduced maintenance costs realized by the use of a PHM system. Therefore an aircraft lifecycle cost-benefit approach is chosen to conduct an economic assessment from an airline perspective. By modeling the aircraft operation based on a weekly flight plan and the maintenance simulated as discrete events within the aircraft life-cycle it is possible to analyze the influence of changes in operational reliability on aircraft utilization and the net benefit for the operator. To show the potential benefits of PHM systems within different aircraft systems (ATA-Chapters) a parameter variation of a notional aircraft system has been performed on a 150-seat short-range aircraft. Effects based on PHM have been modeled by a variation of mean times to repair (MTTR), mean times between unscheduled removals (MTBUR) and the aircraft price. The results show the monetary potential for an airline, depending on the increase of investment cost, and reduction of NFFs and repair time of the chosen system.

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Nomenclature

A/C = aircraft

ASM = available seat mile

ATA = Air Transport Association

DOC = direct operating cost

ESAD = equivalent still air distance

FC = flight cycle

FH = flight hour

h = hour

LCC = lifecycle cost

LRU = line replaceable unit

MTBF = mean time between failures

MTBUR = mean time between unscheduled removals

MTOW = maximum takeoff weight

MTTR = mean time to repair

NFF = no-fault-found

NPV = net present value

PHM = prognostics and health management

ROI = return on investment

RUL = remaining useful life

TAT = turn around time

TOW = takeoff weight

I. Introduction

IN a competitive environment, airlines are continuously obliged to improve their business to stay profitable. Focusing on aircraft operation, this can be achieved by reductions in operating costs and increases in revenues. Significant potential to realize further cost reductions and increases of aircraft availability are seen in the area of maintenance. Maintenance accounted for an average of 9.9% of the total operating expenses between 2008 and midyear 2010 of US air carriers [1]. Additionally, scheduled aircraft maintenance reduces the availability of the aircraft to generate revenues. Unscheduled maintenance not only consumes time, but can also cause delays and cancellations of flights. 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-founds (NFF) [3]. An item removal is classified as NFF when no fault is exhibited during subsequent acceptance test [4]. To determine the value of operational reliability and its influence on operating costs and losses of revenues, all relevant aspects have to be included in an evaluation. Therefore the impact of new technologies, especially in the area of maintenance, should be fully understood to determine its net value.

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 [5-8]. 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 [6, 8]. Feldman et al. [8] 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.

II. Methodology / Approach

A. Aircraft lifecycle cost-benefit analysis model

While the different (commercial) stakeholders in the air transportation system may have conflictive goals, something they all have in common is the striving for profit maximization. New technologies for the air transportation system must therefore not only lead to technical improvements, but have to primarily 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 [9, 10]. Standard DOC methods account for crew expenses (cabin and cockpit), landing and navigation fees, maintenance, fuel, depreciation, insurance, 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.

The lifecycle cost-benefit method used in this study goes beyond DOC and models relevant cost and benefit parameters along the system lifecycle. The goal of this approach is to supply first statements on economic viability and feasibility of a technical system during the design phase. An availability of this information enables a more robust decision-making in the early stages of technology development, a specific control of the development process and consequently a reduction of development time and costs. The lifecycle cost-benefit model focuses on the perspective of an airline and includes methods to account for costs and revenues. These costs and revenues depend strongly on the utilization of an aircraft. Therefore costs and revenues are calculated in the model based on a primary model to simulate flight and maintenance plans and technical delays, as illustrated in Figure 1.

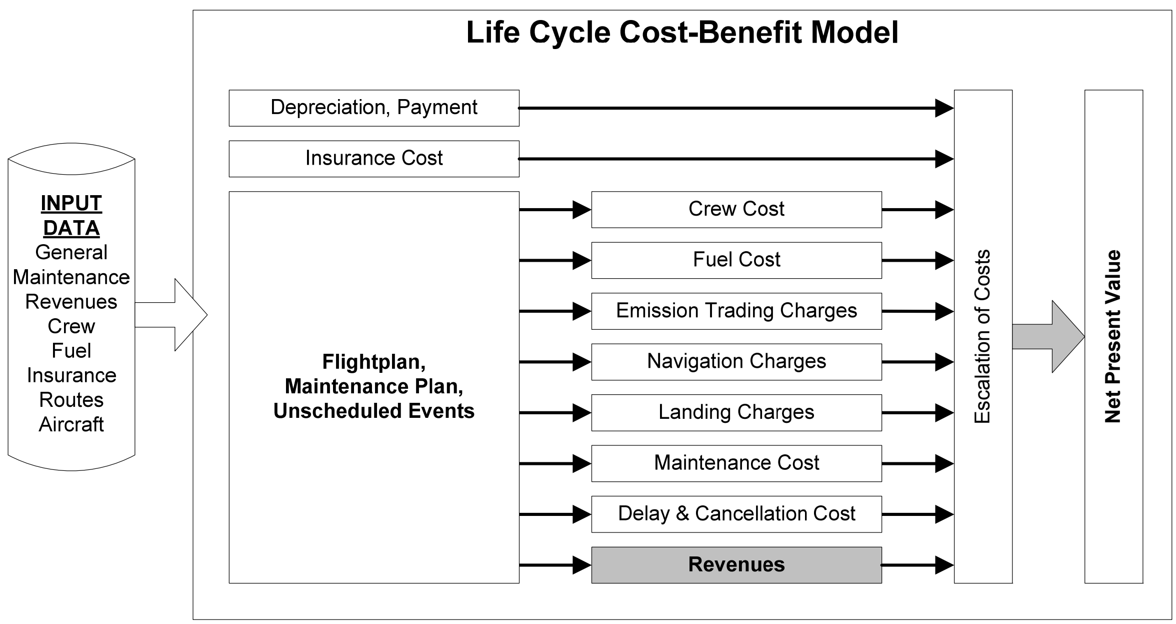

Figure 1: Structure of lifecycle cost-benefit model

The model is based on a top-down approach and primarily includes parametric and statistic interrelationships of technical parameters and costs. For more detailed studies, bottom-up approaches are added to the model, e.g. in the case of component-related studies. By this, especially the improvement rate in cost-effectiveness compared to a preceding system in operation or an alternative concept can be estimated.

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. Revenues are modeled using statistics with consideration of flight's great circle 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.

All mentioned aspects (as shown in Figure 1) form the airline's cash flow over the aircraft life, which can be summarized as net present value (NPV). The NPV is a common metric to quantify a project's net-contribution to wealth [11] 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 Equation 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.

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

To provide a flexible evaluation method and assess technologies with varying influences, the lifecycle cost-benefit model provides adaptable structures and input parameters.

B. Aircraft utilization and maintenance model

To account for influences of technologies on the aircraft availability within the lifecycle cost-benefit method, the utilization of the aircraft during its lifecycle is modeled. Routes are considered based on the aircraft cycle time including flight time, taxi and runway operation times, and turnaround time. Building up an aggregate lifetime flight schedule based on provided route data, scheduled maintenance is considered depending on discrete, interval-based events. Intervals are specified by flight hours (FH), flight cycles (FC), time (years, months, days), or a combination of these parameters. Each event has a specific ground time, during which the aircraft's utilization is set to zero while creating time discrete costs to the airline for labor and material. For the computation of the utilization and maintenance schedule, line and base maintenance for airframe, heavy components and engines are taken into account. To consider operating experience and maturity effects in maintenance, the possibility of interval escalation during the lifecycle is provided in the model.

Unscheduled maintenance is considered on an accumulated ATA-Chapter level or by a provided component database. Using the modeled lifetime flight schedule, unscheduled events are simulated based on mean times between unscheduled removals (MTBUR), aircraft related mean times to repair (MTTR) and the quantities per aircraft. Component failures related MTTRs greater than the specified turnaround time of the aircraft induce delays. These delays reduce the operational availability and thereby the flight schedule while creating costs to the airline for labor, material and passenger delays. The correlation of weekly availability, utilization and occurring maintenance costs as modeled are illustrated in Figure 2. The weekly availability is based on seven 24 hour days and is reduced by night curfews at airports when no flight operations are allowed. 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. Depending on maintenance intervals base maintenance is modeled, reducing the availability and therefore the utilization of the aircraft by the required down-times while related costs are added. A final adjustment of the utilization and cost is made by unscheduled events resulting in the net utilization. The down-times of the unscheduled events depend on the respective MTTRs.

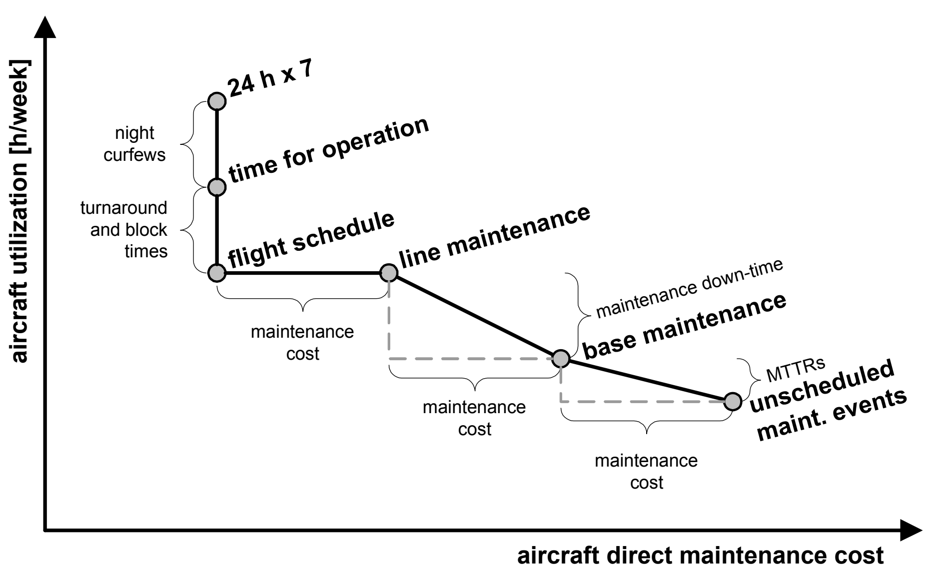

Figure 2: Calculation of availability and maintenance cost.

To consider the influence of maintenance strategies and component reliabilities on spare part provisioning, related inventory costs are modeled. The presented model does not differentiate between participation in a component pool and an airline's own component inventory.

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. [12]

III. Application of lifecycle cost-benefit model

To apply the presented approach, a cost-benefit analysis of a PHM system for a notional aircraft system has been selected. The central purpose of a PHM system is the estimation of the RUL of an item and the provision of advanced warnings of failures. The RUL estimation function requires a health assessment and a failure prediction capability. The prediction process consists of the steps degradation detection, fault diagnostics and degradation extrapolation which finally provide the RUL of the monitored items [13].

Potential benefits which can be achieved by the use of PHM have a wide scope. Prognostic concepts can positively influence the areas safety, maintainability, logistics, lifecycle costs, system design and analysis, and reliability of a product [14]. The benefits, which can be achieved in a specific application, depend on the current maintenance concept and the influence of the monitored item on the safety and operational reliablity of the aircraft. An overview of influences of PHM with economic effects within the aircraft lifecycle is presented in Table 1.

Table 1: Benefits and costs of PHM

Benefits	Costs
Minimizing unscheduled maintenance	Development
Reduction in no-fault-founds	Product manufacturing
Reduction of logistics cost	Infrastructure
Minimizing the loss of remaining life	Operation
Reduction in repair cost	

A complete lifecycle simulation allows incorporating all relevant factors and influences of a new technology regarding the NPV of the aircraft. This general modeling approach not only allows a direct comparison of a PHM implementation to a reference but also combinations of e.g. PHM technology with new scheduled maintenance concepts or with alternative operation concepts.

Proposed Methodology of an economic assessment of PHM

For this study the relevant impacts of a PHM system have been identified and implemented into the aircraft lifecycle cost-benefit model. The estimations of the RUL allow an adapted maintenance concept for the monitored systems. Maintenance will be shifted from corrective or preventive events to predictive events based on estimated RUL. It is assumed in this study that the prognostic horizon is long enough to rectify the predicted failure during the next operational free time period (e.g. night stop-over). This means delays and cancellations due to unscheduled events with repair times greater than the aircraft turn-around-time (TAT) can be avoided. As described in section II, an increased operational reliability allows for more revenue flights in the aircraft lifecycle. Delay and cancellation costs are assigned to an unscheduled event to consider extra expenditures (e.g. passenger delay compensation and costs, and other additional cost) [15]. The associated costs of an unscheduled event depend basically on the type of the airline (e.g. network carrier or low cost carrier), the size of the aircraft, and the repair time. The time of occurrence of a failure during the aircraft rotation has an impact on the costs as well (e.g. failure occurs before first flight of the day vs. failure occurs before last flight of the day).

In the case of a preventive maintenance concept with fixed intervals, a shift to a predictive concept leads to less component replacements due to a higher utilization of the RUL. The aircraft operator can benefit from this by less overall maintenance events, increased aircraft utilization, and reduced spare parts demand.

The health assessment capability of PHM leads to a reduction of NFF and shorter failure rectification times. While the failure distribution of a component and the related mean time between failures (MTBF) are not influenced by PHM, a reduction of NFF leads to an increased MTBUR. This results in less unscheduled events (and possible delays and cancellations) and reduced spare parts demand. A NFF not only produces unnecessary costs in line maintenance and aircraft operation, but also can cause high costs in the component shops. Every LRU removed from an aircraft is sent to a component shop. The existence of a NFF can only be revealed after the completion of a component test program on a special test facility. Furthermore, the health assessment capability enables shorter failure rectification times by a distinctive failure identification and localization. This reduces the expected MTTR and therefore leads to decreased delay or cancellation probabilities. A summary of potential benefits through NFF reductions is shown in Figure 3.

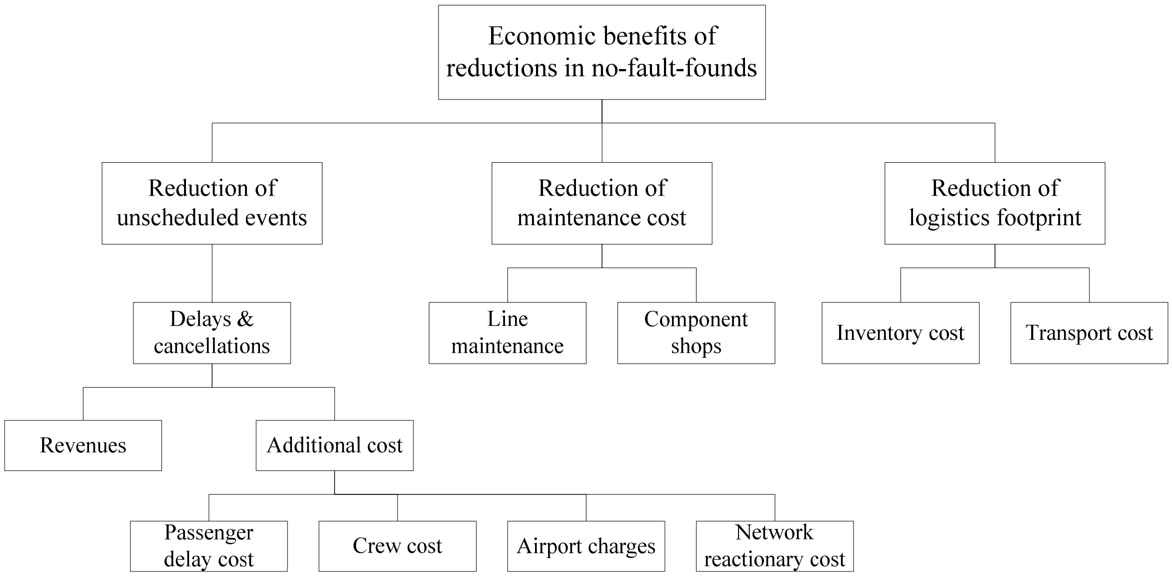

Figure 3: Economic benefits of reductions of no-fault-founds

Following a cost-benefit approach, also the cost of implementation of PHM has to be considered. Implementation cost can be divided in non-recurring and recurring cost. Non-recurring cost are expenses for development of the PHM system (hardware, software, and integration). Recurring cost are product manufacturing cost, infrastructure cost, and sustainment cost (i.e. additional expenses for data collection and archiving, logistics cost of PHM structures, and financial costs).

Costs and benefits associated with using PHM are summarized in Table 1. In this study it is assumed for simplification reasons that the implementation of a PHM system results in a higher aircraft price but no additional recurring costs arise.

IV. Analysis and Results

The lifecycle cost-benefit analysis of a PHM system has been performed using a reference aircraft operated on a specified mission. The assumptions within this study are presented first, followed by a description of the analytical steps applied to assess the economic impact of the PHM system. Afterward the results are presented and interpreted.

A. Reference aircraft and input values

The analysis is based on a 25-years lifecycle of a 150-seat short range aircraft, which technical parameters are held constant during this study. Economic values not specifically mentioned refer to current public available values. As a reference route, a flight from Toronto (YYZ) to Atlanta (ATL) was chosen as presented in Table 2 [16]. The 129 minutes of block time split up to 109 minutes of flight and 20 minutes of taxiing. The cabin layout includes 12 business class and 138 economy class seats, which are serviced by 2 pilots and 3 cabin crew attendants. Cost, time of occurrence, and check mean downtime are based on data available in maintenance, repair and overhaul related databases [17].

Table 2: Fuel burn performance of A320 aircraft equipped with CFM56-5A/5B series engines [16]

City-pair	Aircraft	Engine model	MTOW *[lbs]*	TOW *[lbs]*	Fuel burn *[US.gal.]*	Block time *[min]*	ESAD *[nm]*
YYZ-ATL	A320-100	CFM56-5A1	145,504	140,568	1,519	129	722
YYZ-ATL	A320-200	CFM56-5A1	162,040	143,289	1,551	129	722
YYZ-ATL	A320-200	CFM56-5A3	166,450	143,289	1,551	129	722

To account for costs of passenger delay to the airline, a value of approximately 0.41 US$ per average passenger and average delay minute is used, as identified by Eurocontrol [18]. This value includes 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. The reference aircraft list price is defined as 76,500,000 US$ and reduced by an assumed discount rate of 30%.

B. Analytical steps

For the analysis of the economic potential of PHM systems, a notional aircraft system was defined. The system includes 10 different components, defined by representative quantities per aircraft, MTBURs, aircraft MTTRs, repair costs and spare part prices as listed in Table 3. First a reference calculation was performed based on the presented data with no variation of the system data. The analysis of the net benefit of a PHM system was implemented by a variation of MTBURs and MTTRs, representing reductions of NFFs and shorter failure rectification times inducing decreasing delay probabilities respectively, as discussed before. Assuming a component with a MTBF of 60,000 FH and a NFF-rate of 50% is equivalent with a MTBUR of 30,000 FH (see *Component 1* in Table 3). If a complete NFF avoidance is assumed the number of unscheduled removals is reduced by 50% (i.e.

MTBUR is increased by 100% and equals the component's MTBF). Reductions of MTTRs in the model are partly caused by true shortenings of failure rectification times, while predominantly influenced by the shifting of unscheduled events to operational free time periods. To account for the implementation cost of the PHM system the aircraft price was modulated. It is assumed that the operating cost of the PHM system can be neglected. The specific variation of parameters is listed in Table 4.

Table 3: Input-Parameter of observed pseudo-system

Component	Part-No.	Quantity per A/C	MTBUR *[FH]*	MTTR *[h]*	Repair Cost *[US$]*	Spare Price *[US$]*
1	1000	1	30000	1.0	6500	65000
2	2000	1	18000	1.5	2850	4800
3	3000	3	12000	2.0	3500	18000
4	4000	2	40000	2.0	3200	14000
5	5000	2	8500	2.5	1200	12500
6	6000	4	6000	3.0	1200	12500
7	7000	1	20000	1.5	4000	55000
8	8000	3	10000	1.0	1000	6000
9	9000	2	7000	3.5	1600	50000
10	10000	4	14000	2.0	2000	36000

Table 4: Variation of parameters

Analysis	Increase in aircraft price *[%]*	Increase of MTBURs *[%]*	Decrease of MTTRs *[%]*
1	0	0	0
2	0	0 to 100	0 to 100
3	0	0 to 100	100
4	0.1	0 to 100	0 to 100
5	0.1	0 to 100	100
6	0.2	0 to 100	0 to 100
7	0.2	0 to 100	100
8	0.3	0 to 100	0 to 100
9	0.3	0 to 100	100

For increases in aircraft price from 0% to 0.3% calculations are performed for varying reductions in NFF. This results in increases of component MTBURs from 0% to 100%. To limit the number of necessary calculations in this study and to allow a consolidated presentation of the results, the reductions in NFF (i.e. increases of MTBUR) and the decreases of MTTRs are varied simultaneously. It has to be mentioned, that in principle there is no interrelation between these two parameters. A second set of calculations is conducted for each increase in aircraft price in combination with a decrease of MTTRs of 100% (i.e. no technical delays are assumed). This scenario reflects the theoretical optimum of the failure prediction capability of the PHM. In this case it is assumed that every upcoming failure is predicted early enough to allow a replacement of the deteriorated LRU without interrupting the regular aircraft operation.

C. Results

The changes in NPV for an aircraft with varying relative improvements of MTBURs and MTTRs through PHM compared to the reference are shown in Figure 4. The relative improvements vary from 0% to 100%. While the solid lines reflect the change in NPV for a parallel variation of both MTBURs and MTTRs, the dashed lines are based on variation of MTBURs with MTTRs set to zero, to account for no technical delays. In reality this would mean a 100% success rate of the PHM enabling a shift of maintenance from corrective to predictive events. It can be seen that the two curves for a fixed aircraft price converge with increasing improvements of MTBURs and MTTRs. Consequentially, calculated NPVs are equal, when the improvements reach 100%, because input values are identical in these situations. The calculations are performed for four discrete aircraft prices with increases between 0% and 0.3%, to determine the influence of varying aquisition cost of a PHM system. As expected, the highest net benefit with about 250,000 USD can be achieved in this study, when no increase of the aircraft price and an improvement of 100% for MTBURs and MTTRs are assumed. With an increase of the PHM-acquisition cost up to 0.2% of the aircraft's price and no technical delays (i.e. MTTR = 0), the investment in the PHM system is profitable with any improvement rates in MTBURs. Furthermore it can be seen from the solid NPV-curves, that growing PHM-acquisition cost require increasing improvements in MTBURs and MTTRs to reach the break-even. Apparent fluctuations of the solid NPV curves are caused by the applied time discrete modeling. In general a decrease of the MTTR leads to a higher utilization. However, it is possible that occurrences of several delays during one week cause a decrease in utilization, while single delays do not necessarily impact the weekly utilization. A comparison of the intersection points of the dashed and the solid curves with the ordinate in Figure 4, reveals the ratio of contribution of the two variables. When reading out the intersection points for a price increase of 0%, it can be seen that the shift from corrective to predictive maintenance leads to maximum increase in NPV of 150,000 USD over the aircraft lifecycle (represented by the distance between intersections of dashed and solid NPV curves with the ordinate). The net benefit of a NFF-reduction causes a maximum additional NPV of 100,000 USD (represented by the distance between the intersection of the dashed curve with the ordinate and the maximum increase in NPV of 250,000 USD).

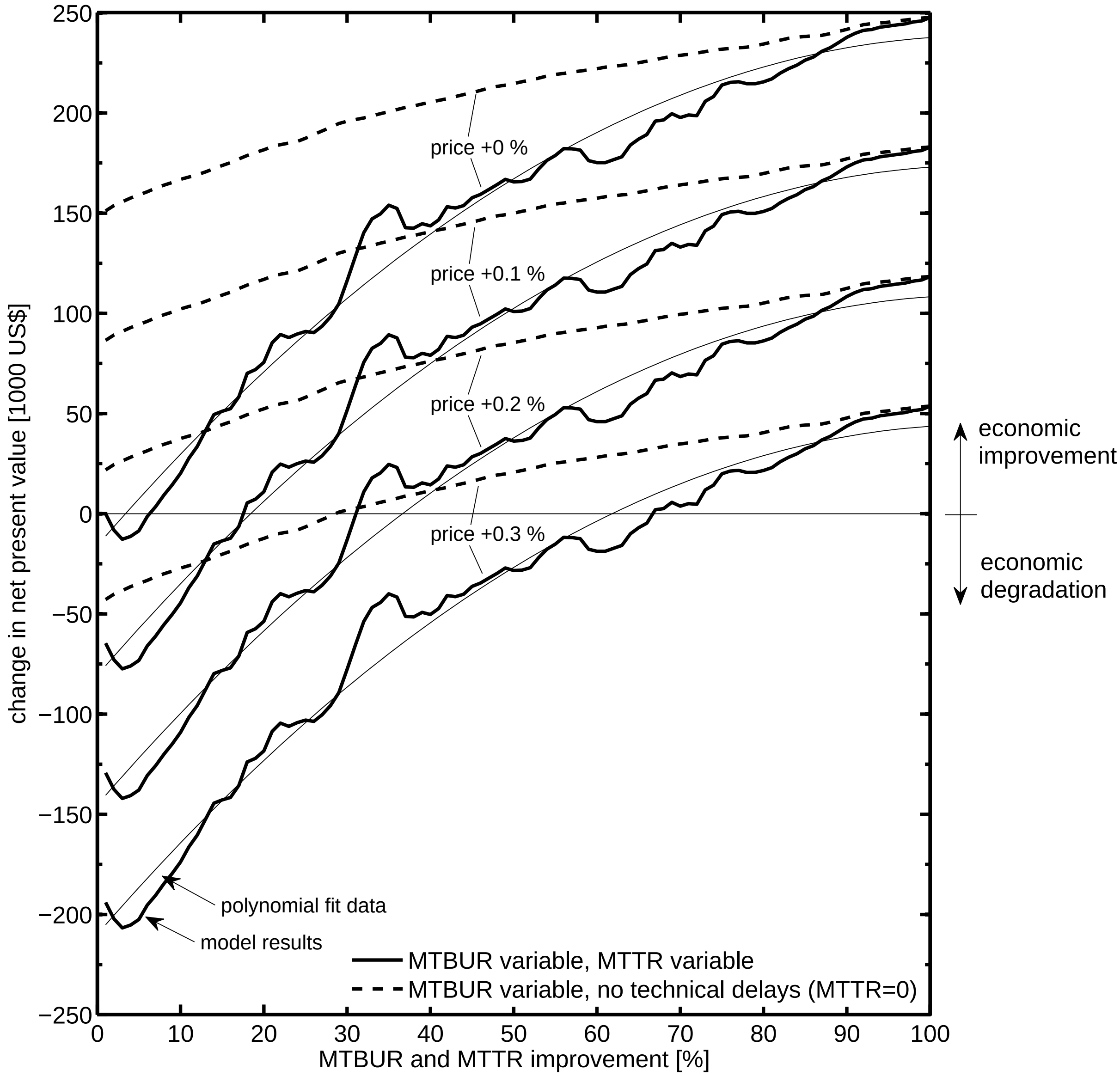

Figure 4: Change of net present value (NPV) by variation of MTBUR, MTTR and aircraft price.

Similar to the changes in NPV the potential reductions in DOC per available seat mile (ASM) are shown in Figure 5. Increases of PHM-acquisition cost up to 0.2% of the aircraft's price show improvements in DOC for all variations of MTBUR, when MTTRs are assumed to be zero. The decreases of DOC per ASM are caused by reductions of maintenance and delay cost, and by slightly reduced capital cost per ASM due to increased utilization. A higher utilization also increases total revenues, while revenues per available seat mile stay constant. In analysis no. 3 of Table 4 with maximum reduction in NFF and no technical delays the additional revenues account for 1,610,000 US$ produced by 64 additional revenue flights over the aircraft lifecycle of 25 years.

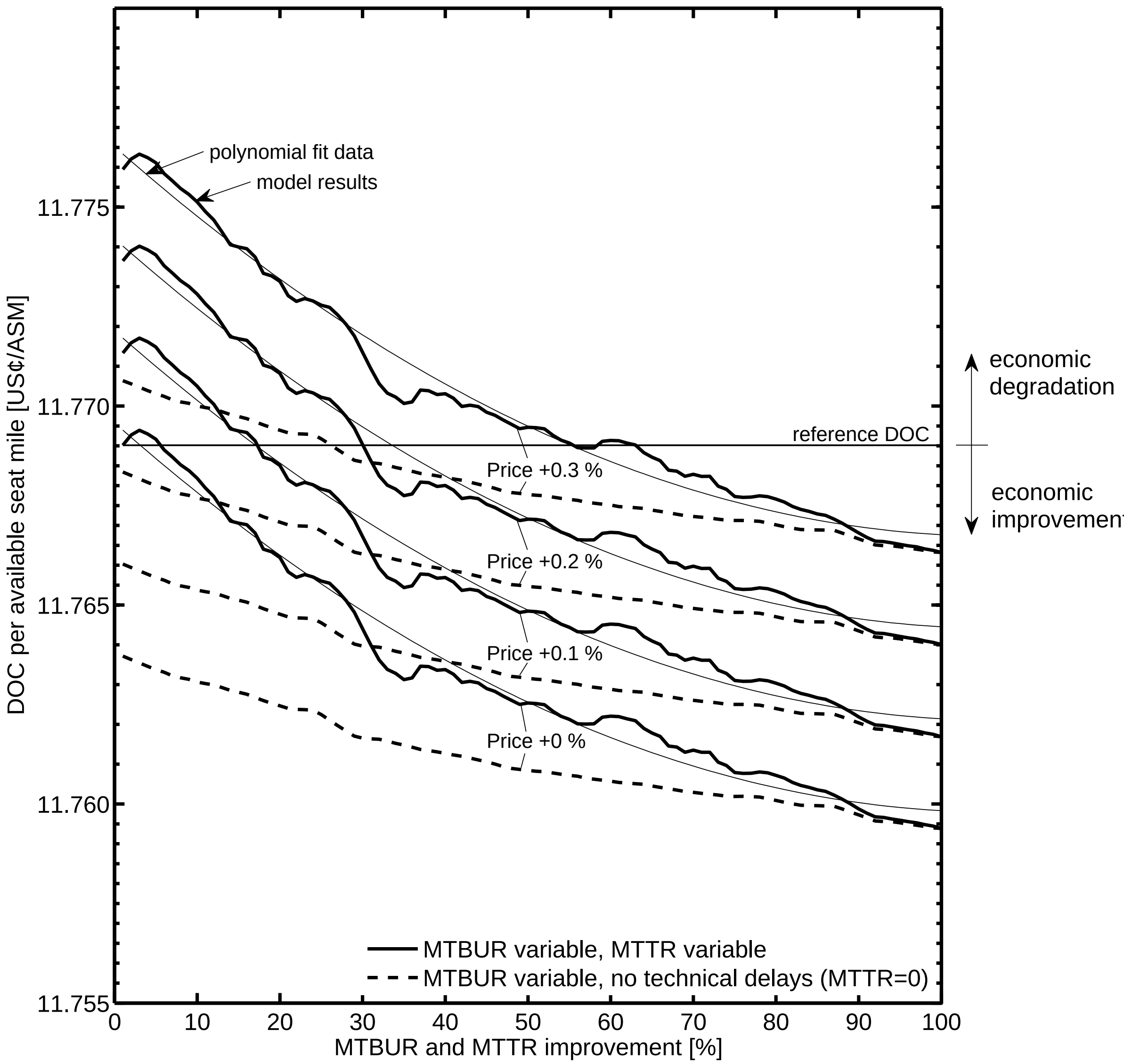

Figure 5: Change of DOC per available seat mile by variation of MTBUR, MTTR and aircraft price

For the notional system the analysis shows improvements necessary at a given aircraft price to achieve an overall economic improvement for an airline.

V. Conclusion and Outlook

This study presents an aircraft lifecycle cost-benefit analysis of a PHM system. The proposed methodology allows calculating the impact of PHM on costs and revenues within an aircraft's lifecycle. Results show the profitability of PHM in a notional system by accounting for impacts on operational reliability and costs. The unscheduled maintenance events have been simulated based on predefined MTBURs and costs in this study. Therefore the results are valid for this specific system and assumptions and should be validated and expanded in studies using real datasets. It can be seen from this analysis that already a PHM implementation on single aircraft systems can produce significant economic benefits for an airline. But the change in NPV, which can be reached, reacts sensitive on varying prices of the PHM system and on the number of operational interruptions avoided by the use of PHM. The presented methodology is able to give fundamental requirements for a PHM implementation in order to generate a profit improvement of an airline.

The net benefit of a technology, e.g. PHM, depends on the system itself, the aircraft, and on the operational scenario of the aircraft. Therefore further studies should be conducted to investigate the impact of additional input parameters, e.g. to account for different operational scenarios on the profitability of PHM more in detail. It is supposed that the maximum benefit of a PHM application can only be achieved by considering further aspects of maintenance-strategies and aircraft operation that are tailored to PHM needs.

Currently the aircraft lifecycle cost-benefit model is based on a weekly flight schedule of a single aircraft. To broaden the scope of application of the methodology, daily flight schedules and fleet influences should be implemented in the future.

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