AN ANALYSIS OF THE INFLUENCE OF NETWORK EFFECTS ON LIFECYCLE BASED AIRCRAFT TECHNOLOGY ASSESSMENT

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Abstract

Assessing the anticipated economic performance of a product is an important part in the development and decision making process. This is especially true for businesses operating in low-profit and high-cost environments such as airlines. Frameworks and tools that aid in this process typically focus on direct operating cost (DOC) or lifecycle cost (LCC) of a single aircraft. However, airlines rarely operate only one aircraft and to transfer the singular results to the complete fleet is not necessarily as simple as a multiplication. Therefore, the assessment framework LYFE (Lifecycle Cashflow Environment) developed by DLR had to be revised and modified in order to evaluate technologies on fleet level. This paper presents the new fleet assessment capability and demonstrates it on an assessment of Hybrid Laminar Flow Control (HLFC). For this study, HLFC was applied as a retrofit on the horizontal and vertical tailplane of Lufthansa's A330 fleet during their D-check. The analyses comprise a fleet wide and time dependent fuel burn evaluation, average maintenance cost and overall economic feasibility. Combined with the LYFE inherent discrete event simulation, this modification enables the inclusion of network effects into detailed technology assessment.

Keywords

Technology Assessment, Overall Economic Assessment, Fleet, Hybrid Laminar Flow Control, Modification, Retrofit, Maintenance

ABBREVIATIONS

ALCCA	Aircraft Lifecycle Cost Analysis
AMRP	Aircraft Maintenance Routing Process
ASDL	Aircraft Systems Design Laboratory
CER	Cost Estimation Relationship
CPI	Consumer Price Index
DLH	Deutsche Lufthansa
DOC	Direct Operating Cost
D_{km}	Flown distance in kilometres
F_{kg}	Fuelburn in kilograms
JU	Joint Undertaking
HLFC	Hybrid Laminar Flow Control
HTP	Horizontal Tail Plane
IDG	Integrated Drive Generator
LCC	Lifecycle Cost
LYFE	Lifecycle Cashflow Environment
NPV	Net Present Value
OEA	Overall Economic Assessment
RDTE	Research, Development and Testing
SFC	Specific Fuel Consumption
VTP	Vertical Tail Plane
WLCC	Whole Lifecycle Cost

1 INTRODUCTION

Strategic fleet decisions are usually associated with a very high capital investment by the airline and can have both positive and negative effects on the company over many years. A priori assessments of possible aircraft substitutes enable operators to get a rough economic impact estimation and facilitate the selection of different technologies. Historically, Direct Operating Cost (DOC) methods are used for this. As their application and what they consider is limited to some extent, alternatives such as Lifecycle Cost (Benefit) analyses received more attention in the past few years [1]. In this context, the Institute of Maintenance, Repair and Overhaul from DLR developed the tool Lifecycle Cash Flow Environment (LYFE), a modular framework dedicated to capture the impact of various alterations (e.g. technologies) throughout the lifecycle. The core module AirLYFE considers the aircraft as the object for assessment from the operator's perspective. LYFE includes a discrete event approach to simulate and analyze all relevant cash flows (costs and revenues) throughout the product lifecycle. Within AirLYFE, discrete events include, but are not limited

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to, aircraft purchase, flights performed, scheduled and unscheduled line and base maintenance with corresponding downtime, various monthly recurring costs and the the resale of the aircraft. The level of detail varies with the level of information available to users. If little or no knowledge is available, AirLYFE's results essentially fall back to DOC methods, while more detailed cost/revenue methods and more complex interrelations are easily implementable due to LYFE's modularity.

Like most technology evaluation environments, LYFE considers one aircraft at a time and neglects fleet effects. Few other models do consider fleets but are usually developed with a different focus, e.g. to select best routing schedules and aircraft types for a specified market demand [4, 7, 27]. However, airlines rarely buy just one aircraft or operate only one type. Quite contrarily, most airlines operate a wide mixture of aircraft types to fulfill the market demands and to maximize their profit [6]. Aspects such as the temporal planning of longer base maintenance and "spare" aircraft can play a major role for airlines. Therefore, the framework LYFE is currently being extended to be able to model these fleet effects.

Based on this extension, the aim of this study is to shed light on the influence of network effects on an exemplary, fleet wide technology assessment. Thereby, identified key parameters will be varied and sensitivities analyzed, intending to demonstrate the fleet module.

The procedure to do so can be divided into two parts. The first one is to restructure the frameworks way of working, i.e. to enable the discrete event simulation for an entire fleet. This requires an adjustment of most of the functional module definitions. It includes the assignment of flights to aircraft while respecting certain rules for routing frequencies and maintainability requirements. Another crucial point is the regular "live" adjustment of this assignment within the simulation. This includes an heuristic optimization which aims to minimize the overall downtime while considering maintenance base locations and, if required, reassignments of flight schedules. The second step is to test this fleet module by simulating an exemplary airline which aims to equip their existing fleet with a fuel saving technology. The outputs cover overall economic metrics such as the Net Present Value but also average maintenance cost and fuel burn differences.

With the extension of the existing aircraft lifecycle simulation environment to include fleet representation, the application of technologies can be assessed on a more realistic level. It also extends the assessment capabilities towards other procedures and effects, such as valuing aircraft commonalities and pilot cross-qualifications.

The remainder of this paper is structured as follows. Section 2 provides some fundamentals and gives some examples of literature dealing with the topics of the fleet assignment problem and economic technology assessment. Section 3 describes the required changes in the present framework for enabling fleet-level studies. For the purpose of demonstrating the capabilities, Section 4 contains an exemplary application of Hybrid Laminar Flow Control as Retrofit on a realistic fleet. The work concludes with a summary and outlook in Section 5.

2 FUNDAMENTALS AND LITERATURE OVERVIEW

The aim of this section is to introduce some relevant background for a) how airlines assign individual flights to aircraft within their fleet, b) how aircraft technologies are typically evaluated economically, and c) how the use case of Hybrid Laminar Flow Control works.

2.1 Schedule Planning Process

The business of airlines involves a large capital investment with a very low profit margin of usually only 3-7 % [28]. In order to ensure profitable or benefit-maximizing flight operations, many airlines use a structured but complex planning process. A subdivision into less complex sub-problems for more efficient and optimized scheduling allows a sequential implementation of this process [4, 25].

For the tool modification described in this paper only the sub-process of *schedule planning* is important. The schedule planning process creates a flight plan for each aircraft, which contains all flights and the respective exact times of the flights as well as all necessary maintenance activities. According to Lohatepanont [25] and Liang and Chaovalitwongse [22], the schedule planning process can be divided into further partial planning steps. These processes deal with the decision which markets are to be served (route development) with which frequency (schedule design) and the distribution of all planned flights among the different fleets[1] of the airline according to the estimated capacity demand (fleet assignment). The flights are then spread among the aircraft in a fleet, taking into account the maintenance requirements of the respective aircraft (aircraft routing).

[1] Because of the similarities between aircraft of the same type and the differences between aircraft of different types, airlines usually treat all their aircraft of the same type as one fleet [31].

According to Liang and Chaovalitwongse [22] the goal of the Aircraft Maintenance Routing Process (AMRP) is to find a maintainable rotation[2] of the airplanes and represents a subordinated optimization problem of flight planning.

There are different approaches to group the solving methods of the aircraft routing problem. Lacasse-Guay, Desaulniers, and Soumis [20] distinguish a possible grouping in view of three different main business processes that regulate the assignment of aircraft tail numbers to the planned flight routes. On the other hand, Liang and Chaovalitwongse [22] distinguished a grouping on the basis of the underlying mathematical models, which contain network flow based models, string based models and heuristic algorithms.

Network flow-based models are oriented on a model developed by Clarke et al. [7]. The time-space network for a given fleet is represented by a directed graph. By forming an Euler tour[3] in the time-space network and the subsequent elimination of all paths of the service violation[4], the maintenance conditions can be fulfilled and the route problem can be solved.

String-based models create flight plans so that the length of the rotation corresponds to the time required until the next maintenance. String scheduling[5] is therefore always done from maintenance event to maintenance event. These models formulate the problem as a *traveling salesman problem*.

Heuristic algorithms are according to Domschke and Scholl [10] the procedure for the evaluation of good acceptable solutions of optimization problems. In contrast to optimization procedures that find an *optimal solution* of the problem, heuristics determine a solution that is estimated to be *sufficiently good*. A large use of heuristics takes place especially where optimization methods fail because of too high computational effort for practical problems or where the problem areas are poorly structured and difficult to understand [37]. The use of heuristic algorithms to solve the AMRP can be implemented in very different ways.

For example, Desrochers and Verhoog [9] developed a savings heuristic with the aim of finding a fleet composition and a set of routes with a desired minimum in total cost.

Al-Thani, Ahmed, and Haouari [34] have compared an exact model with a metaheuristic approach to solve the AMRP. The comparison showed that the exact model provides optimal solutions for cases with up to 354 flights and eight aircraft, but fails beyond that, while the heuristic approach provides consistently high-quality solutions with short computational times.

Eltoukhy et al. [12] have developed four different heuristic models for solving the AMRP. Three of the proposed models are based on metaheuristics to solve the problem. These approaches have been selected for their efficiency in solving routing problems. The fourth model was developed on the basis of identified possibilities for improvement of the metaheuristics and represents an algorithm that is individually adapted to the problem. A comparison of the four models shows that the individually developed solution algorithm is superior to the metaheuristics both in the search for a better solution and in the mapping of the airline's profitability.

2.2 Economic Technology Assessment

The aim of Overall Economic Assessments (OEA) of aircraft designs, aircraft technologies, operational procedures, or more generally, products, is to determine which alternative (out of two or more) is economically superior. This subsection deals with some legacy and state of the art methods for OEA and subsequently describes the framework that is developed by the DLR Institute of Maintenance, Repair and Overhaul.

2.2.1 Methods and Tools

Historically, aircraft designs and technologies are assessed using so-called DOC methods. DOC methods are sets of equations that require parameters of the aircraft (e.g. operating empty weight) or utilization (e.g. average flighthour per flightcycle) and provide estimations on the average DOC (e.g. annual airframe maintenance cost). These equations, or Cost Estimation Relationships (CERs), are based on regression analyses of airline fleet and financial data and are valid for a steady state operation of the aircraft, only (i.e. somewhere between the 5th and 15th year of operation) [33]. Due to their quick implementation and fast evaluation, DOC methods are implemented in many commercial and non-commercial tools (e.g. in Refs. [24] and [15], respectively).

Bodegraven [5] from Boeing and Schnieder [33] from Airbus provide a general introduction into DOC

[2] A maintainable rotation is a sequence of contiguous flight routes assigned to a particular aircraft. It begins and ends at the same location, the length of the rotation corresponds to the duration of a previously defined period of time and the maintenance regulations of the aircraft manufacturers and supervisory authorities are respected [25, 31].

[3] An Euler tour describes a path in which each leg is contained exactly once and the start and end points are identical [13].

[4] A service violation path is a path whose duration exceeds the length of a previously defined period of time [22].

[5] A string is a sequence of connected flights, which starts immediately after a maintenance check, ends with the next maintenance check and can last a certain number of days [20].

methods and state some areas of applicability. Comparative overviews of DOC methods are given in Ali and Al-Shamma [3], Lee, Li, and Song [21], and Pohya, Wicke, and Hartmann [30]. Readers interested in examples of typical applications of such methods are referred to Elham and Tooren [11] and Xu et al. [40]. A typical (or at least questionable) usages can be found in Cuerno-Rejado, Alonso-Albir, and Gehse [8] and Martinez-Val et al. [26], where a blended wing body aircraft and a joined wing are assessed, respectively. Both applications clearly deviate from conventional aircraft designs and the results have to be interpreted with caution.

In the past decades, costing methods shifted towards a more holistic approach [1]. Some involve performance degradation through decades of operation [18], and others cross the barrier of the stakeholder, taking the manufacturing and disposal into account[6] [16]. Since both approaches can be found under the term of Lifecycle Cost (LCC), it is suggested to name the latter Whole Lifecycle Cost (WLCC) for differentiation purposes[7]. WLCC typically comprise cost for Research, Development and Testing (RDTE), manufacturing (recurring and non-recurring), operation and maintenance, support, as well as disposal.

One of the earlier studies dealing with WLCC in the field of Aeronautics can be found in Johnson [16]. The author optimized an subsonic aircraft's wing for lowest DOC, (W)LCC, and other cost figures, covering short-range, medium-range and long-range aircraft. Results showed significant differences between the aircraft designs, highlighting the relevance of figure of cost merit chosen. Another well known WLCC approach is the Aircraft Lifecycle Cost Analysis (ALCCA) and was first developed by NASA and then optimized by the Aerospace Systems Design Laboratory (ASDL) from GeorgiaTech [41]. ALCCA not only calculated the different (whole) lifecyle cost, but spread them over the lifecycle and thus was able to include the time value of money. For studies focusing on degradation and LCC, see Justin and Mavris [19], where the authors implemented a simplified engine degradation model and investigated the increase of fuel burn throughout decades of operation. Other examples for LCC methods are given in Thokala, Scanlan, and Chipperfield [35] and Thokala, Scanlan, and Chipperfield [36] for aircraft design optimization and in Wen et al. [39] for spacecraft systems.

2.2.2 LYFE and AirLYFE

DLR developed its own python-based framework for OEA of various products of different maturities called LYFE. The derivative of LYFE that deals with aircraft as object of interest and the operator as the main stakeholder is named AirLYFE. AirLYFE uses a discrete event simulation of the aircraft's life from the order until sale or decommissioning, including specific flight events, line and base maintenance checks, unscheduled and unforeseen events, as well as periodically recurring payments.

The two main requirements for the development were a) ensuring a wide range of customization and applicability, and b) enabling the quantification of not only primary (i.e. direct) impacts of a change in the lifecycle, but also secondary ones (i.e. those "down the river"). A primary effect for instance would be the reduced fuel cost due to a more efficient aircraft, whereas a secondary effect would consider the repercussions between these fuel savings and degradation mitigation measures, quantifying the effect on the overall operating cost. The first requirement was fulfilled by a hierarchical modular design: Through well defined interfaces, almost all parts of the code can be replaced (from a specific method up to a complete module), without touching the source code. The second requirement was the reason for the discrete event approach, where each event has a trigger definition with a functional relationship to other events and circumstances throughout the simulation. The most simple example is the trigger of a scheduled maintenance event, which monitors the aircraft's current flighthours, flightcycles and age. It is important to mention that the current state of AirLYFE foresees one single aircraft and can not, apart from running multiple (independent) AirLYFE instances in parallel, evaluate products on a fleet level.

For studies using AirLYFE, refer to Refs. [29, 30]. A pure methodology publication on AirLYFE is currently being worked on and estimated to be available in 2021.

2.3 Hybrid Laminar Flow Control

HLFC aims to reduce the aircraft drag and hence fuel consumption by moving the transition from laminar to turbulent flow from its original position near the leading edge up to 60% of the chord length [17], see Fig. 1. It can be applied on the wings, horizontal and vertical tail planes, as well as the engine nacelles and comprises two main elements:

[6] This approach is sometimes described as with "cradle to grave".

[7] Note that this differentiation is already typical for other sectors that deal with long-term investments, such as civil engineering [1, 38].

- Active suction of the boundary layer in the forward region of the airfoil, usually through a microperforated or slotted skin material, and
- An airfoil geometry with carefully designed pressure distribution properties, damping turbulence mechanisms.

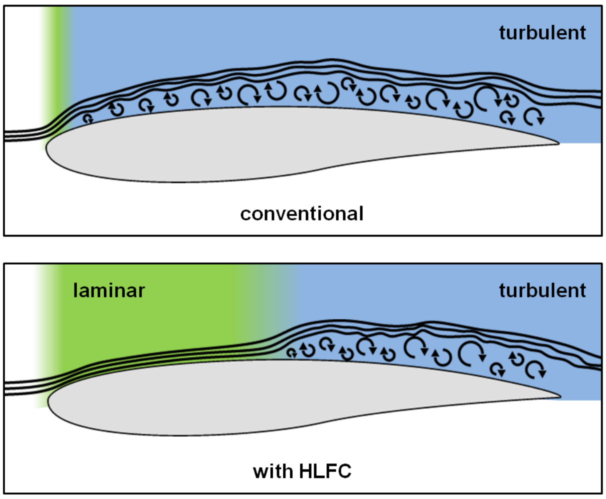


Figure 1: Illustration of the laminar turbulent transition for conventional and HLFC airfoils

For the suction part, additional systems such as compressors are required[8]. These compressors need electrical energy, which are taken from the Integrated Drive Generator (IDG). Besides this, the systems and materials used introduce additional weight, which counteracts against the intended fuel savings. From OEA perspective, a beneficial HLFC application needs to overcome additional negative effects. These include an increased RDTE effort, which may translate in an increased purchase or modification price, as well as additional maintenance, which, at the very least, means inspection of the systems and surfaces. Furthermore, a realistic and tenable OEA needs to include off-design aspects such as in-service degradation.

3 REQUIRED TOOL MODIFICATION

As mentioned before, the current version of AirLYFE is not able to simulate a fleet of aircraft. Although it would be possible to simply multiply the results by the number of aircraft or run several AirLYFE instances in parallel, network effects and other interrelations can not be captured. To address these shortcomings, the basic structure of LYFE had to be modified. This section provides some details on the two main areas of modification: a) the one enabling simultaneous runs while keeping the discrete event paradigm and b) the one representing a more realistic airline operation, where the route assignment is heuristically improved.

3.1 Adjustment for Simultaneous Discrete-Event Simulation

In it's current state, AirLYFE makes use of a so-called "Event Calendar", which contains each event in the aircraft's life. This calendar is updated each time an event occurs, and with that, the time in the simulation is updated as well. This time is saved in a "Global Clock", which starts with the date and time of ordering the aircraft and ends with the date and time of its resale. As all modules within AirLYFE work with this global clock, this paradigm had to be kept for the present capability modification at hand. This however required some conceptual changes in the way the modules are called. Figure 2 shows the flowchart of the fleet version.

The first change required a *list of aircraft* and a query of *which aircraft is next*. The main idea behind this was to keep maximum compatibility with the existing modules, i.e. inside a module such as `maintenance`, it is irrelevant whether a fleet is simulated or just one aircraft. The selection of the next aircraft is based on its global clock. It is always the aircraft with the earliest *time* on the watch that is selected next. For instance, if, at a given time in the simulation, the three aircraft A, B, and C have their own global clocks set at 12:30, 12:14, and 13:03, respectively, aircraft B is selected and the overarching simulation time is set to 12:14. After appending a maintenance event to this aircraft, the query yields aircraft A and sets the watch to 12:30. This procedure is continued until the end of the simulation.

With this modification, the discrete event paradigm following discrete but varying timesteps is kept, ensuring the capability of capturing primary and secondary impacts as described before. Additionally, at any given time, the simulation knows where which aircraft is located, enabling the next required change: The route assignment improvement.

3.2 Adjustment for Improved Route Assignment

With the previously described change, the route assignment itself would still be exactly the same as in the single-aircraft-version of LYFE. Under certain circumstances this can lead to situations that are not realistic. For instance, the simulation would put all aircraft

[8]An overview of what is needed for an HLFC application and their effect on the overall efficiency is given in Young [42].

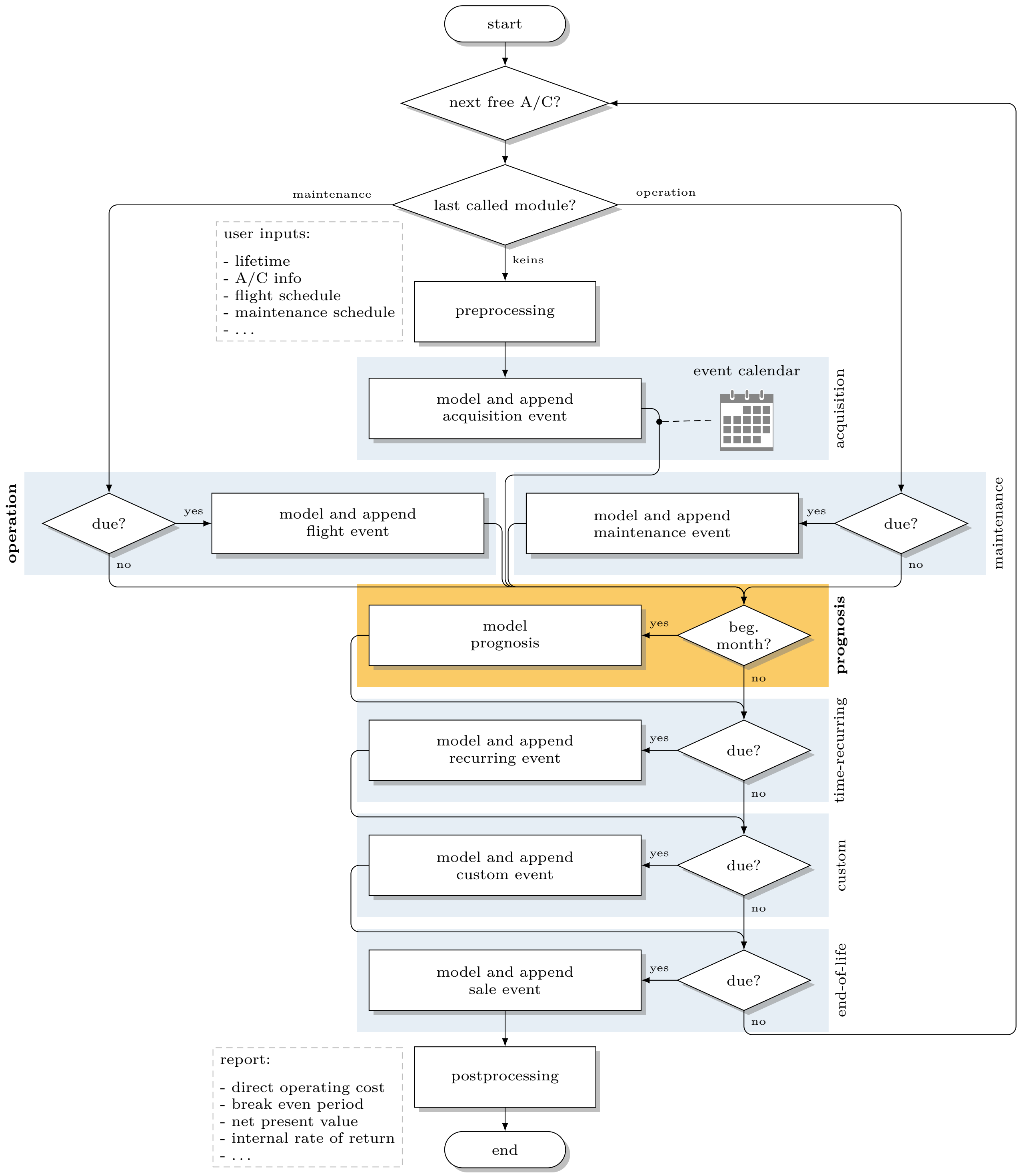
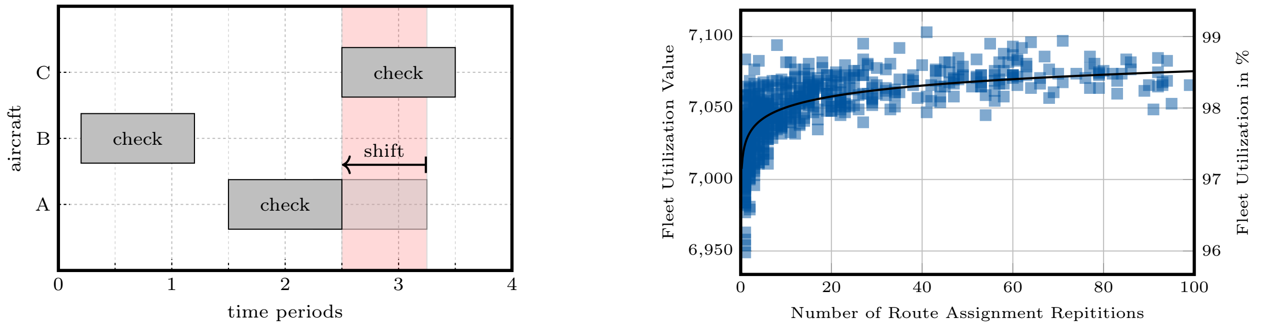


Figure 2: Updated modular structure of AirLYFE for being capable of s fleet wide simulation.

of a fleet into maintenance at the same time, if their intervals were exceeded at the same time. To reach a higher level of realism, a prognosis module was developed. The prognosis module, which is highlighted in Figure 2, is called periodically (e.g. monthly) and fulfills two functions:

(a) Avoid unnecessary downtimes on fleet-level by adjusting the base maintenance schedule.
(b) Further improve the utilization on fleet-level by assigning an "optimal" route schedule to each tailsign.

For the first function (a), the module estimates when which aircraft requires (base) maintenance. This is done for a given prognostic horizon (e.g. three



(a) Illustration of a check shift due to unnecessary fleet wide downtime.

(b) Fleet wide utilization vs. number of iterations of route assignment.

Figure 3: Visualization of the two main effects of the prognosis module.

months). The fleet wide maintenance schedule is then analyzed to identify any avoidable simultaneous downtime of two or more aircraft. An example of such an avoidable situation is given in Fig. 3 (a), where aircraft A and C are both expected to need a C-Check at the first week of March, leaving aircraft B to do all the flights in that week. In this situation, the module moves the C-check of one of those aircraft forward, e.g. by a week. Codewise, this is implemented using a binary vector (0: in the air, 1: on ground) for each aircraft where each entry represents a time period in the prognosis. These vectors are then added and analyzed by the algorithm for reducible "peaks", i.e. periods where many aircraft are on ground simultaneously.

The second function (b) incorporates an heuristic algorithm for improved fleet wide utilization, which is depicted in Fig. 4. Based on the user input, which specifies a demand of flights for a given period, the module randomly assigns the routes to the aircraft. This is done for each aircraft for the whole prognosis period. On its own, this would just result in a random, not improved utilization. This is where the heuristic approach comes into play. It calls the route assignment multiple times, and within each run, the fleet wide utilization is estimated and compared to the previous run. If it improved, this current schedule is saved and the iteration repeats. The exit condition for this algorithm is simply a fixed number of iterations. This approach is rather pragmatic but easily understandable and adjustable. In order to find an acceptable trade-off between calculation time and utilization "optimization", the number of random assignments was varied and analyzed. Figure 3 (b) shows the asymptotic behavior, where the fleet utilization is plotted against the number of runs[9]. Based on this quick investigation, the number was fixed to 30. However, it should be noted that in most cases the initial "guess" of a flight schedule already provides a high utilization[10] and future modifications may disable this function.

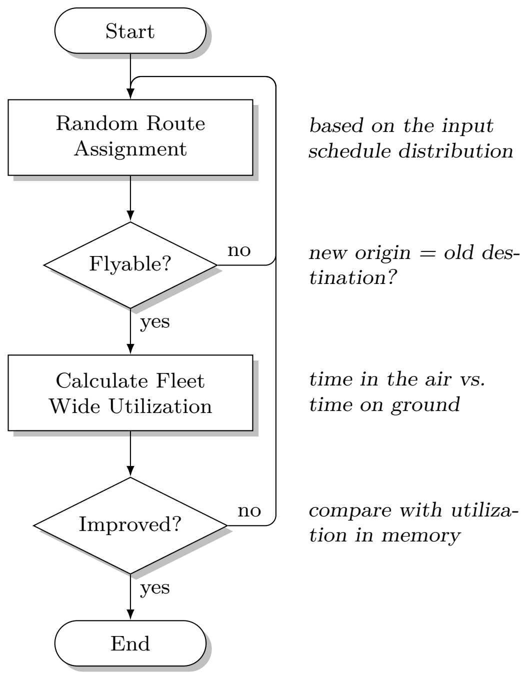


Figure 4: Flowchart of heuristic route assignment

4 ASSESSMENT OF HYBRID LAMINAR FLOW CONTROL AS RETROFIT

In order to demonstrate the described LYFE-modifications, an exemplary fleet wide technology assessment is presented. This section describes and

[9]The fleet utilization unit is an internally calculated number with a sole algorithmic interpretation.

[10]In the example of Figure 3 (b), the initial guess (i.e. after one run) provided a fleet wide utilization, which is more than 95 % of the value that is reached after 100 runs.

discusses the boundary conditions, assumptions and results of the study.

4.1 Reference Fleet

General: As usual, the reference case to which the results are compared to, has to be well defined. In this study, the A330 fleet from Lufthansa (DLH) was reconstructed. At the time of writing DLH operates 15 A330-300 on long-haul routes, all based in Frankfurt (FRA). Figure 5 shows the hub and spoke network of this fleet[11].

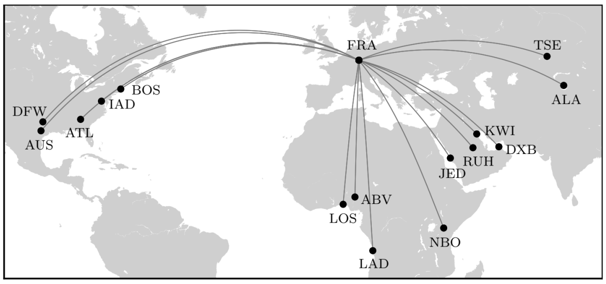


Figure 5: Route network of the 15 A330-300 operated by Lufthansa as of 2019.

These routes were extracted and for simplification reasons treated as great circle trajectories, i.e. no wind or time correction was applied. For the estimation of fuel burn, a range-dependent model was used, calibrated on actual documented fuel burns of the A330-300 [2, p.18]. This model is described in Eq. 1, assuming a constant payload of 80 %.

$$F_{\mathrm{kg}} = 7.18\frac{\mathrm{kg}}{\mathrm{km}} \cdot D_{\mathrm{km}} - 1924\,\mathrm{kg} \tag{1}$$

Entry into Service: The entries into service of the 15 aircraft were obtained from a commercially available database[12], ranging from March 2004 to March 2014. All aircraft have 255 seats, divided into three classes (business, premium economy and economy), which is a necessary information for the ticket price function of AirLYFE.

Maintenance Schedule and Cost: For this study, only scheduled maintenance was considered. The intervals in terms of flighthours, flightcycles, and age were obtained from *Aircraft Commerce* [2]. This also included cost for each line, base, and engine maintenance as well as for heavy components which are typically out of phase tasks. For the downtimes of the heavier base maintenance, a simplified interpolation of Eurocontrol's generic downtime table from Ref. [14] and the number of check tasks in Ref. [2] was used.

4.2 HLFC Fleet

General: The study case foresees the application of HLFC on the horizontal (HTP) and vertical tail planes (VTP) as a retrofit during the C8, which occurs after about 8-10 years of operation. Therefore, the fleets are *identical* in terms of fuel burn and cash flow until the first retrofit happens[13]. To estimate the fuel burn of the HLFC aircraft, the impacts of drag reduction, mass increase and power offtake were analyzed beforehand using an aircraft performance estimation tool[14]. Afterwards, the impact on fuel burn was translated back to AirLYFE. For this, HLFC was assumed to be working throughout the trajectory, i.e. not only in cruise. Furthermore, no degradation of any kind was considered, giving this study quite an optimistic character.

HLFC Inputs: To determine the overall fuel savings of an HLFC aircraft compared to the fully turbulent A330-300, three values were required (mostly based on Young [42]):

- **a) Drag Reduction:** For the drag reduction, the transition position was assumed to be 25 %, since a retrofit does not change the airfoil and thus can not ensure laminarity for areas significantly beyond suction. Based on a similar study of a Boeing 757 (where HLFC was also applied to the HTP and VTP), the resulting overall drag reduction was assumed to be 2.1 %.
- **b) Mass Increase:** For the additional mass due to systems and materials, which comprise ducts, valves, controls, the perforated skin and other elements, an overall increase of roughly 700 kg per aircraft was assumed.
- **c) Power Offtake:** With the suction areas on the HTP and VTP of an A330-200 of about 31 m^2 a power offtake of 53 kW would be required. This was then translated into an increase of specific fuel consumption using an efficiency of 80 % for the motor, compressor and IDG as well as an

[11] Note that this is a slightly simplified flight schedule. The original one included very few short-range flights, which have been filtered out for simplification reasons.

[12] See `https://www.cirium.com/`.

[13] To ensure the exact same route assignment, which is essentially random in nature, a "random seed" was set and held identical for both simulations.

[14] See Piano-X, `https://lissys.uk/PianoX.html`.

assumption of about 0.5 %/100kW increase of specific fuel consumption (SFC).

Depending on the range, the resulting fuel savings of an HLFC aircraft lie between 0.8 % (for a range of 1000 NM) and 1.5 % (for a range of 5400 NM). For the economic assessment, additional information had to be estimated:

- **d) Cost of the Retrofit:** This was estimated using the additional mass and the help of the aircraft price estimation equations of two DOC methods (Liebeck et al. [23] and Risse et al. [32]). These yielded an averaged value of abouot \$1M, on which a typical discount of 40 % was applied. This lead in an overall retrofit cost for the operator of \$610k.
- **e) Duration of the Retrofit:** For this parameter a plain engineering guess was used, i.e. additional two days of work on top of the 30 days downtime.
- **f) Additional Maintenance:** Similarly to point e), a best guess of an increase of 10% of cost and duration of the weekly line maintenance was used. This reflects cleaning the surfaces, inspection for damages and clogging as well as performing minor repairs.

4.3 Other Inputs

For completion reasons, some other assumptions and boundary conditions are documented here:

- A lifetime of 20 years for each aircraft was assumed. With the spread of 10 years of acquisition (reflecting the actual orders of DLH), this results in a 30 year overall simulation time from 2004 to 2034.
- For the unknown fuel price of the years 2020 to 2034 a scenario from the US Department of Transportation named "Reference" was used. This ranges from \$2.34/gal to \$2.82/gal.
- All inputs are correctly inflated using the consumer price index (CPI). All results are discounted accordingly.
- The discount rate for the Net Present Value (NPV), the key metric of this study, was chosen to be 8%.

As AirLYFE uses many other inputs such as crew operating scenarios, ticket prices, or curfews, the above mentioned list is not complete. However, they all have been set to the default values, which aim to be neither optimistic nor pessimistic. Furthermore, most of the impact of these parameters cancel each other out when comparing the results.

4.4 Results

The results of the exemplary assessment are analyzed in four steps. First, the fuel efficiency of both fleets are compared to one another. Second, the average maintenance cost are looked into and third, the economic efficiency in terms of net present value of is discussed. Lastly, a simplified sensitivity analysis is performed to determine the max. price which the manufacturer may ask for while ensuring that the operator still benefits from the HLFC retrofit (under the assumptions made).

Fleet Wide Fuel Efficiency

Figure 6 shows the average fuel burn in litres per pax, 100km and aircraft for both fleets. Three periods are distinguishable. In the first period, no aircraft (regardless of the fleet) is equipped with HLFC. Therefore, the fuel efficiencies are identical. In the second period, which is where the aircraft are being modified with HLFC during their heavy check, the fuel efficiency of the HLFC fleet decreases slightly by 0.86 % from originally $2.81\,\mathrm{L}/(\mathrm{pax}, 100\mathrm{km})$ to $2.79\,\mathrm{L}/(\mathrm{pax}, 100\mathrm{km})$. The current number of aircraft with HLFC is indicated with the dashdotted line. The third and last period is characterized again by a steady behavior.

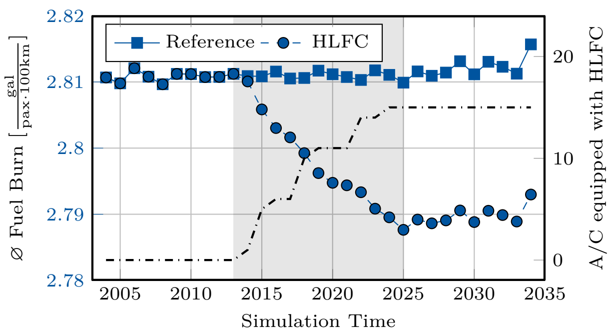


Figure 6: Average fuel burn in litres per pax, 100km and aircraft of the reference and HLFC fleet.

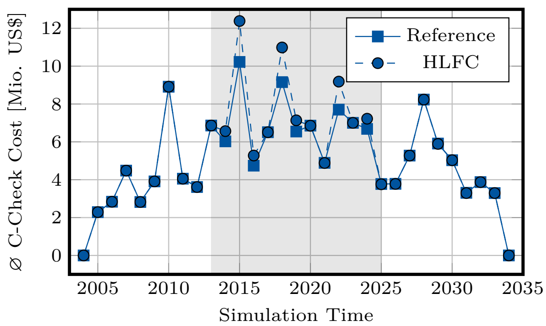
Although the fuel efficiency was modeled in a fairly simple matter, i.e. through a calibrated range-dependent model, this figure nicely illustrates the discrete event and object behavior of LYFE. With the actual entries into service and scheduled C8 checks, the impact of the gradually increasing number of HLFC aircraft is easily identifiable and quantifiable.

Maintenance Cost

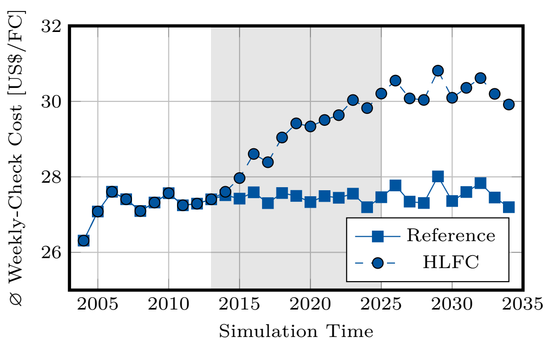
The impact on the maintenance cost is twofold: (a) As the retrofit itself costs about \$610k, the total cost of the C8 check is expected to be higher for the HLFC fleet compared to the reference fleet. (b) Due to the modeled additional inspection, the average cost for the weekly check is also expected to increase for an HLFC application. Both effects are shown in Fig. 7. Again, the three periods are easily distinguishable. In subfigure (a), the average C-check cost per aircraft are identical in the first and last period, whereas a difference can be observed in the modification period (gray area). Depending on the number of aircraft modified per year, this difference is sometimes higher (e.g. in 2015) and sometimes zero (e.g. in 2021). The average weekly check cost, which are shown in subfigure (b), have some similarities to the fuel efficiency development of Fig- 6. While being identical first, the cost gradually increase in the modification period and the difference remains constant in the last period.

Net Present Value (NPV)

The economic results are shown using the NPV, which incorporates costs, revenues, and the time value of money. If the HLFC NPV is higher than that of the reference fleet, this retrofit would be categorized as economically favorable (for the operator). If it is negative, the conventional fleet is economically superior. Figure 8 (a) shows the fleet wide NPV (black line) as well as the NPVs of each single aircraft (blue dashed line) for the reference. The overall NPV decreases in the first years as the aircraft in the fleet are ordered but do not operate yet, i.e. the cash flow only consists of the payment costs. It continues to stay negative until 2011, which represents the break even year. From then on, the operation of this fleet adds value to the investor. At the end of the simulated lifetime, the NPV asymptotically reaches its final value[15]. From the plots of the aircraft specific NPVs, the three periods where Lufthansa ordered the A330s are identifiable (i.e. 2004, 2007 and 2012). Note that the later operated aircraft yield a smaller NPV solely due to the time value of money.

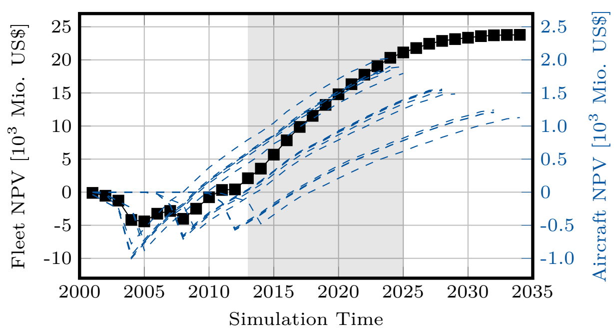


(a) Average cost for a C-Check.

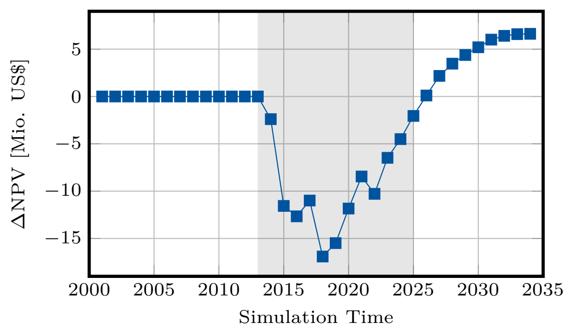


(b) Average cost for a weekly check (per Flightcycle).

Figure 7: Simulated maintenance cost for both analyzed fleet.



(a) NPV of the reference fleet and each aircraft in it.



(b) Delta in NPV between the reference and HLFC fleet.

Figure 8: NPV curves of the simulated fleets.

[15]Note that the absolute value is not of primary interest in this context, as technology assessments rely on comparisons, where most assumptions and uncertainties cancel each other out.

The economic impact of the HLFC retrofit on fleet level is shown in Fig. 8 (b) as ΔNPV. Until the year 2013, the ΔNPV remains zero, as both fleets are identical. From then on, it becomes negative, reaching a minimum value of \$16M in 2018. This represents the impact of the modification cost, which are not yet outweighed by the fuel efficiency savings. The curve then gradually increases and becomes positive in the year 2026, marking the fleet wide break even year for this particular technology. At the end of the simulation, the HLFC modification yields an extra of \$6.5M to the operator, fleet wide. Compared to the reference NPV, it is clear that this impact is rather small and the investment should only be pursued if the associated risks are negligible.

Retrofit Cost Sensitivity

As the price for the modification plays a major role in the OEA, it's sensitivity is analyzed. For this, the initial estimation of \$610k was varied from 50% to 200% and the impact on the fleet ΔNPV was tracked. Figure 9 shows this result. Under the circumstances assumed, the application of HLFC on the HTP and VTP has to cost less than \$770k (about 125% of the initial guess) for the operator to make a profit. The overall sensitivity can be summarized as a loss of ΔNPV of \$430 per \$100 increase of the retrofit cost. Note that his sensitivity is highly impacted by many inputs, such as the fuel price scenario and the assumed HLFC maintenance schedule, which were held constant at this point.

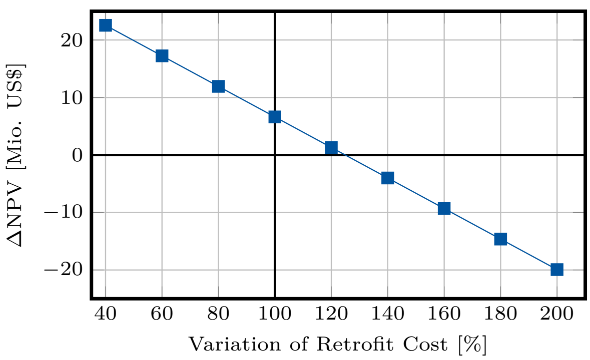


Figure 9: Sensitivity of ΔNPV for a variation of the retrofit cost.

5 CONCLUSIONS AND OUTLOOK

In the present study, a modular and discrete event based framework for overall economic assessments was modified for fleet wide evaluation capabilities. The required steps were documented and involved a prognosis algorithm, which not only shifts maintenance checks of single aircraft, but also assigns an improved flight schedule to each aircraft. Both aspects are based on heuristics, aiming to reduce the overall fleet wide downtime. Besides the development of this prognosis module, the work in this study included a partial restructuring of the framework, which was necessary to ensure the original discrete event approach. For exemplary purposes, the capabilities were tested and shown on a fleet wide assessment of Hybrid Laminar Flow Control. This technology was assumed to be implemented as a retrofit during the C8 check of Lufthansa's A330-300 fleet. Impacts on the fuel efficiency, maintenance cost and overall economic feasibility were analyzed and discussed. Under the stated assumptions, the investigated application of HLFC on the HTP and VTP was evaluated to be economically beneficial for the operator. With this use case, the framework modification for fleet wide technology assessments successfully passed a sanity check. Future work will mainly focus on reducing the runtime, for instance through an adaption of the heuristics.

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DISCLAIMER

The results, opinions, conclusions, etc. presented in this work are those of the authors only and do not necessarily represent the position of the JU; The JU is not responsible for any use made of the information contained herein.

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REFERENCES

[1] R. K. Abdelhalim Boussabaine. *Whole Life-cycle Costing*. John Wiley & Sons, May 8, 2008. 264 pp. ISBN: 9780470759158.

[2] Aircraft Commerce. "Aircraft Owner's & Operator's Guide: A330-200 /-300." In: *Aircraft Commerce* 57 (Apr. 2008), pp. 8–39.

[3] R. Ali and O. Al-Shamma. "A Comparative Study of Cost Estimation Models Used for Preliminary Aircraft Design." In: *Global Journal of Research In Engineering* (2014).

[4] M. Bazargan. *Airline Operations and Scheduling*. Taylor & Francis Ltd, Aug. 28, 2010. 302 pp. ISBN: 978-0-7546-7900-4.

[5] G. V. Bodegraven. "Commercial aircraft DOC methods." In: *Aircraft Design, Systems and Operations Conference*. American Institute of Aeronautics and Astronautics, Sept. 1990. DOI: 10.2514/6.1990-3224.

[6] P. Clark. *Buying the Big Jets : Fleet Planning for Airlines. Fleet Planning for Airlines*. 3rd ed. Abingdon, Oxon New York, NY: Routledge, an imprint of the Taylor & Francis Group, 2017. 372 pp. ISBN: 9781315570662.

[7] L. Clarke et al. "The aircraft rotation problem." In: *Annals of Operations Research* 69 (1997), pp. 33–46.

[8] C. Cuerno-Rejado, L. Alonso-Albir, and P. Gehse. "Conceptual Design of a Medium-sized Joined-wing Aircraft." In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 224.6 (Dec. 2009), pp. 681–696. DOI: 10.1243/09544100jaero648.

[9] M. Desrochers and T. Verhoog. "A new heuristic for the fleet size and mix vehicle routing problem." In: *Computers & Operations Research* 18.3 (1991), pp. 263–274.

[10] W. Domschke and A. Scholl. *Heuristische Verfahren*. Wirtschaftswissenschaftliche Fakultät Friedrich-Schiller-Universität Jena, 2006.

[11] A. Elham and M. J. L. van Tooren. "Winglet Multi-objective Shape Optimization." In: *Aerospace Science and Technology* 37 (Aug. 2014), pp. 93–109. DOI: 10.1016/j.ast.2014.05.011.

[12] A. E. Eltoukhy et al. "Heuristic approaches for operational aircraft maintenance routing problem with maximum flying hours and man-power availability considerations." In: *Industrial Management & Data Systems* (2017).

[13] L. Euler. "Solutio problematis ad geometriam situs pertinentis." In: *Commentarii academiae scientiarum Petropolitanae* (1741), pp. 128–140.

[14] EUROCONTROL. *Dynamic Cost Indexing - Aircraft maintenance - marginal delay costs*. Technical Discussion Document. Eurocontrol, 2008.

[15] L. U. Hansen, W. Heinze, and P. Horst. "Blended Wing Body Structures in Multidisciplinary Predesign." In: *Structural and Multidisciplinary Optimization* 36.1 (Nov. 2007), pp. 93–106. DOI: 10.1007/s00158-007-0161-z.

[16] V. S. Johnson. "Minimizing Life Cycle Cost for Subsonic Commercial Aircraft." In: *Journal of Aircraft* 27.2 (Feb. 1990), pp. 139–145. DOI: 10.2514/3.45909.

[17] R. D. Joslin. *Overview of laminar flow control*. Tech. rep. NASA/TP-1998-208705, L-17631, NAS 1.60:208705. Hampton, Viriginia (USA): NASA Langley Research Center, Nov. 21, 1998. 142 pp.

[18] C. Justin, E. Garcia, and D. Mavris. "Aircraft Valuation: A Network Approach to the Evaluation of Aircraft for Fleet Planning and Strategic Decision Making." In: vol. 1. Sept. 2010. ISBN: 978-1-62410-159-5. DOI: 10.2514/6.2010-9061.

[19] C. Y. Justin and D. N. Mavris. "Aircraft and engine economic evaluation for fleet renewal decision-making and maintenance contract valuation." In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 229.11 (Jan. 2015), pp. 2051–2065. DOI: 10.1177/0954410014564403.

[20] E. Lacasse-Guay, G. Desaulniers, and F. Soumis. "Aircraft routing under different business processes." In: *Journal of Air Transport Management* 16.5 (2010), pp. 258–263.

[21] M. Lee, L. K. B. Li, and W. Song. "Analysis of Direct Operating Cost of Wide-body Passenger Aircraft: A Parametric Study Based on Hong Kong." In: *Chinese Journal of Aeronautics* 32.5 (May 2019), pp. 1222–1243. ISSN: 1000-9361. DOI: 10.1016/j.cja.2019.03.011.

[22] Z. Liang and W. Chaovalitwongse. "The Aircraft Maintenance Routing Problem." In: *Optimization and Logistics Challenges in the Enterprise*. Vol. 46. May 2009, pp. 327–348. DOI: 10.1007/978-0-387-88617-6_12.

[23] R. H. Liebeck et al. "Advanced Subsonic Airplane Design and Economic Studies." In: *Contractor Report 195443* (1995). Ed. by N. Aeronautics and S. A. (NASA).

[24] Lissys UK. *Piano-X*. Ed. by D. Simos. 2020. URL: https://lissys.uk/PianoX.html.

[25] M. Lohatepanont. *Airline fleet assignment and schedule design : integrated models and algorithms*. Aug. 2002.

[26] R. Martinez-Val et al. “Optimization of Planform and Cruise Conditions of a Transport Flying Wing.” In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 224.12 (June 2010), pp. 1243–1251. DOI: 10.1243/09544100jaero812.

[27] N. Papadakos. “Integrated airline scheduling.” In: *Computers & Operations Research* 36.1 (2009), pp. 176–195.

[28] B. Pearce. “Profitability and the air transport value chain.” In: *IATA Economics Briefing* 10 (2013).

[29] A. A. Pohya and K. Wicke. “An Impact Assessment of Degrading Elements on the Overall Benefit of Aircraft with Hybrid Laminar Flow Control.” In: *AIAA SciTech 2019*. Jan. 2019.

[30] A. A. Pohya, K. Wicke, and J. Hartmann. “Comparison of Direct Operating Cost and Life Cycle Cost-Benefit Methods in Aircraft Technology Assessment.” In: *SciTech 2018*. Jan. 2018.

[31] X. Qi, J. Yang, and G. Yu. “Scheduling Problems in the Airline Industry. Algorithms, Models, and Performance Analysis.” In: *Handbook of Scheduling*. Taylor & Francis Ltd, Apr. 27, 2004. ISBN: 1-58488-397-9.

[32] K. Risse et al. “Central Reference Aircraft data System (CERAS) for research community.” In: *CEAS Aeronautical Journal* 7.1 (2016), pp. 121–133.

[33] H. Schnieder. “Methode zur Bewertung von Projekten und Technologien im zivilen Flugzeugbau.” In: *DGLR Jahrestagung* (1999).

[34] N. A. Al-Thani, M. B. Ahmed, and M. Haouari. “A model and optimization-based heuristic for the operational aircraft maintenance routing problem.” In: *Transportation Research Part C: Emerging Technologies* 72 (2016), pp. 29–44.

[35] P. Thokala, J. Scanlan, and A. Chipperfield. “Life cycle cost modelling as an aircraft design support tool.” In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 224.4 (2010), pp. 477–488.

[36] P. Thokala, J. Scanlan, and A. Chipperfield. “Framework for Aircraft Cost Optimization Using Multidisciplinary Analysis.” In: *Journal of Aircraft* 49.2 (Mar. 2012), pp. 367–374. DOI: 10.2514/1.C000187.

[37] P. D. J.-P. Thommen and D. M. Siepermann. *Definition Heuristik*. Ed. by G. Wirtschaftslexikon. 2018. URL: https://wirtschaftslexikon.gabler.de/definition/heuristik-34474/version-257976.

[38] C. Viavattene and H. Faulkner. “An Uncertainty Index to Measure the Feasibility of Whole-life Cycle Costing Approach in Flood Risk Management.” In: *Journal of Flood Risk Management* 5.3 (Apr. 2012), pp. 215–225. DOI: 10.1111/j.1753-318x.2012.01140.x.

[39] Y. Wen et al. “A fractionated spacecraft system assessment tool based on lifecycle simulation under uncertainty.” In: *Chinese Journal of Aeronautics* 25.1 (2012), pp. 71–82.

[40] J. Xu et al. “Aircraft Route Optimization for Formation Flight.” In: *Journal of Aircraft* 51.2 (Mar. 2014), pp. 490–501. DOI: 10.2514/1.c032154.

[41] R. Yackovetsky. *Development of Advanced Life Cycle Costing Methods for Technology Benefit/cost/risk Assessment*. Tech. rep. Grant Number NAG-2-2149. Hampton, Virginia: NASA Langley Research Center, Apr. 11, 2002. 79 pp.

[42] T. M. Young. “Investigations into the Operational Effectiveness of Hybrid Laminar Flow Control Aircraft.” PhD thesis. Cranfield University, 2002. 153 pp.