An Assessment of the Economic Viability of Engine Wash Procedures on the Lifecycle Cost of an Aircraft Fleet

Jennifer Wehrspohn, Ahmad Ali Pohya, and Kai Wicke

Deutsches Zentrum für Luft- und Raumfahrt e.V., Hamburg, 21129, Germany
Jennifer.Wehrspohn@dlr.de
Ahmad.Pohya@dlr.de
Kai.Wicke@dlr.de

Abstract

Aircraft operators find themselves in an environment in which the economic and ecological pressure on companies is constantly increasing. To address this, significant improvements of aircraft efficiency are necessary. One way to reduce both operating cost and the environmental impact is to regularly perform on-wing engine washes which reduce the exhaust gas temperature as well as improve aircraft fuel consumption. To estimate the lifecycle impact of engine cleaning procedures, a variety of factors must be taken into account, ranging from environmental to operational. The lifecycle costing method developed by DLR, known as LYFE (Lifecycle Cash Flow Environment), enables the consideration of various factors to investigate the impact of engine washes over the lifetime of an aircraft or fleet. LYFE uses discrete event simulation to model the product lifecycle from order to operation until disposal of an aircraft fleet. For this analysis the tool is extended to separate the lifecycles of the engines and those of the aircraft, which enables the modeling of switching engines among aircraft. To more realistically represent engine fouling and engine performance degradation, representative weather data at airports is also included in the simulation. Using this information, we have developed a prognostics model to monitor the health of the engine, predict the timing of engine shop visits and automatically and dynamically schedule engine wash events. For the latter, three different algorithms varying in the prognostic horizon were developed and compared to one another. The results show that engine washing can improve the time on wing of the engine by up to 2240 flight cycles. Due to lifetime limitations by life limited parts and assumptions within this study, no extension of the service life of the engine can be achieved within the scope of this investigation. On the other hand, the fuel cost could be reduced at an average of 1.2% while the total cost remained the same. With this holistic view of how engine washes within a fleet influence the time on wing of the engine and affect its lifecycle cost a much more realistic statement about this on-wing maintenance action is possible.

1. Introduction

In today's society, the demand for low ticket fares and more environmentally friendly aircraft continues to grow. Reasons for this are the increasing demand of 4 to 5% per year in global air traffic before the Covid19 crisis (Airbus S.A.S., 2021; Boeing, 2021) and the fact that the aviation sector is responsible for about 13% of the transport-related fossil fuel consumption (Brasseur et al., 2016). This is why the European Commission has defined long-term economic and ecological targets in the "Flightpath 2050" as a reaction on European and global level (European Commission, 2011). The pressure on airlines is therefore constantly increasing from both an economic and an ecological point of view. One way to mitigate the situation is to operate the aircraft more efficiently and reduce fuel consumption. Regularly performed Engine Washes (EWs) can reduce the accumulation of dirt in the engine, which reduces the Exhaust Gas Temperature (EGT) and decreases engine wear. The loss of engine power can thus be partially compensated, resulting in a reduction in fuel consumption after an EW (Ackert, 2011; Hutter, 2006). Direct improvement potentials through on-wing washes have already been identified by a few studies, but the secondary effects on the lifecycle, e.g. the influence of a longer Time on Wing (ToW), have not been investigated. In addition to that, the impact of EW processes is often modeled without taking environmental conditions and fleet effects into account.

The objective of this work is to quantify the economic value of EW procedures, taking into account both physical boundary conditions of components and operational considerations of engines. A detailed investigation of the primary and secondary effects and a quantification of lifecycle cost will be performed on fleet level. Particular attention will be paid to the influence on maintenance cost as well as the economic effect of increased ToW. To investigate this problem, an object-oriented and detail-driven Python framework for lifecycle costing is used. This framework, called Lifecycle Cash Flow Environment (LYFE), was developed by DLR and models the entire product lifecycle, which considers ordering as well as operation and disposal of aircraft. In the context of this analysis, LYFE is extended and adapted with a simple Prognostics and Health Management (PHM) process (Bougacha, Varnier, & Zerhouni, 2021) in order to trigger engine maintenance events based on the current engine health status. For this, various parameters that have an influence on the engine's health are taken into account. The engine health statement then forms the basis of the decision as to whether maintenance is necessary or not. In addition, LYFE has been enhanced with the ability to account for engine replacements over the lifecycle. In order to be able to make a statement on EW in the following, the lifecycle of an A320 family fleet is simulated and examined. A reference workflow without any EWs is compared to three differnt prognostic EW triggering strategies, each targeting to minimize the predicted cost per Flight Cycle (FC). Thereby the relationship between the anticipated degradation, the resulting fuel savings potential, the cost of performing an EW, and the time, cost and scope of the next Engine Shop Visit (ESV) are considered. These approaches follow the paradigm of prescriptive maintenance (Liu, Lin, Zhang, & Kumar, 2019), i.e. not only the next required maintenance is predicted, but also recommendations for the optimal use are given.

The remainder of this paper is structured as follows: Section 2 gives a short overview of economic assessments of aircraft and some insights in the lifecycle of an engine. It also shows a brief overview of the recent work addressing EWs. Section 3 deals with the framework used for the assessment. Here the extensions of LYFE as well as the case-specific deterioration and maintenance models are presented. Section 4 of this paper describes the performed studies and related results. This paper concludes with the summary and outlook in Section 5.

2. Fundamentals and Related Work

The intention of this Section is to introduce readers that are unfamiliar with (1) conventional economic assessment methods in aeronautics and the evaluation framework LYFE, (2) on- and off-wing maintenance of aircraft engines, including deteriorating factors and repercussions on the operation and (3) related work dealing with the assessment of engine cleaning procedures.

2.1. Economic Evaluation Methods

Assessments of the economic viability of product alternatives, whether they are specific technologies, operational processes or maintenance strategies, are a vital aid in the decision making process (Mevellec & Perry, 2006). In the aeronautic domain, a variety of different methods and metrics are used, each with their own advantages and drawbacks. What follows is a brief classification of the current state-of-practice in technology valuation as well as a short introduction to the assessment framework at hand. For further information on the former, consider (Curran, Raghunathan, & Price, 2004; Niazi, Dai, Balabani, & Seneviratne, 2005; Altavilla, Montagna, & Cantamessa, 2017). For the latter, a detailed publication is in progress (Pohya, Wehrspohn, Meissner, & Wicke, 2021).

2.1.1. Evaluation Methods and Metrics

In aeronautics, available methods for economic technology assessment are dominated by parametric approaches. As such, the impact of the Object of Interest (OoI) is quantified using a set of Cost Estimation Relationships (CERs), which are based on historic and typically unpublished data. Depending on the content, i.e. considered temporal space and cost elements, these are clustered into Direct Operating Cost (DOC), Lifecycle Cost (LCC), and Whole Lifecycle Cost (WLCC) methods. DOC methods are limited to the settled state of an aircraft and consider cost of ownership, fly-away cost, and maintenance cost. They are the most frequently used method due to their quick evaluation, but lack in terms of level of detail and flexibility. LCC methods focus on the long operational phase, the DOC scope by ageing and deterioration effects as well as an increased level of detail, e.g. by including fleet wide effects or additional cost elements. LCC tools are typically specific to the object of assessment at hand, which leads to a lack of standardized methods in this domain. WLCC methods are similar to the DOC approach but include the manufacturers' perspective by providing equations for production, research and development, and occasionally end of life.

As their name suggests, the above mentioned methods only consider the expenditures affiliated with a product, but neglect its impact on the revenues. Including these enables the calculation of metrics that are familiar to and widely used by investment decision makers. The Net Present Value (NPV) is one of the most frequently relied upon metric and is calculated using the time discrete cash flows CF_t as well as a company or project specific discount rate r, which accounts for the time dependent value, i.e. future cash flows are weighted less than present ones (Brealey & Marcus, 2019). The NPV formula is:

$$\text{NPV} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} \tag{1}$$

Other often complementary used economic metrics are the internal rate of return, return on invest, and time to break even. In the context of assessing maintenance related products, the advantage of these metrics is that they directly capture a potential loss of revenue, e.g. due to delays, unscheduled downtimes or other repercussions.

2.1.2. Lifecycle Simulation Framework LYFE

The underlying framework LYFE was developed to overcome the limitations of the current assessment practices, i.e.:

- The fixed parameter space of the parametric techniques substantially simplifies the complex environment and interactions of participating stakeholders in the air transportation system.
- In-depth analyses of specific technologies exceed the scope of applicability of most generic CERs. This leads to individual frameworks and methodologies which suffer from comparability.
- Delays and other temporal space effects of processes or products (e.g. degradation over time) cannot be taken into account with conventional parametric analyses practices.

LYFE addresses these shortcomings with a customizable, modular, multi-fidelity, and discrete event driven approach. It models the lifecycle of an aircraft from its order through decades of operation and maintenance until its end of life, enabling not only the evaluation of the overall economic effectiveness, but also in-depth operational insights. An exemplary application can be found in (Pohya & Wicke, 2019). In its current status, LYFE considers one aircraft (and one set of engines) at a time, whereas the next update will incorporate fleet wide operations including a management of spare parts and engines (described in Section 3.2) and the methodology as shown in (Pohya, Wehrspohn, & Wicke, 2020). The primarily affected aspects include a restructuring of the event calendar as well as a prognosis algorithm for improved fleet wide utilization, which not only shifts maintenance checks of single aircraft, but also assigns an updated flight schedule to each aircraft on a monthly recurring basis.

An excerpt of the event calendar of an individual aircraft is depicted in Fig. 1, where the discrete events include flights from and to London Heathrow (LHR) as well as a transit, preflight and an A1 check, which are automatically scheduled based on predefined Flight Hour (FH), FC or passed-time intervals.

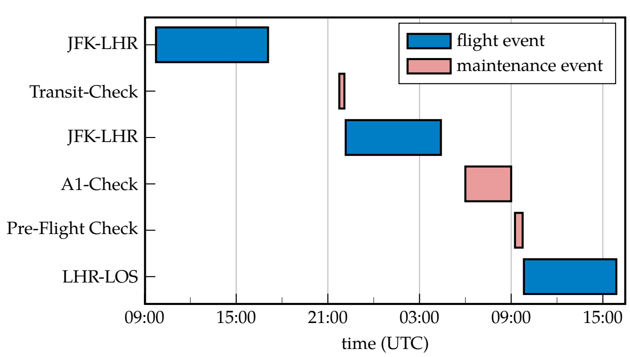

Figure 1. Excerpt of an exemplary event calendar of a London Heathrow (LHR) based long range aircraft

2.2. Deterioration and Maintenance of Aircraft Engines

Aircraft engines are a highly-complex and high-value asset that account for about 20 % of an aircraft's list price[1]. With its main task of providing thrust, reliability and safety aspects are of eminent importance. Therefore, it is not surprising that engine maintenance consumes about 35% - 40% of the airline's Direct Maintenance Cost (DMC) (Ackert, 2011). In a cost reduction effort, operators and maintenance providers have extensively focused on these assets, e.g. by reducing the engine load during take-off or by implementing different restoration measures such as an EW to extend shop visit intervals (Ackert, 2011; Donaldson, Fischer, Gough, & Rysz, 2007). As a basis for the present study, the mechanisms around engine deterioration as well as conventional engine maintenance practices are briefly explained next.

2.2.1. Engine Deterioration

Aircraft engines are subject to a constant exposure to ambient conditions and high loads, significantly influencing their performance, degradation, and expected lifetime. Arguably the most influential (and co-dependent) factors are the (a) Engine Flight Hour (EFH) to Engine Flight Cycle (EFC) ratio, (b) the take-off thrust rating and derate level, as well as (c) the operating environment (Ackert, 2015; Hutter, 2006):

(a) Compared to longer EFH/EFC ratios, engines operated at shorter flight segments tend to have a shorter time on wing due to a higher portion of flight time with take-off and climb power settings.

(b) Operating engines at lower thrust levels (e.g. through derating) leads to lower core temperatures and subsequently lower thermal stress, slowing down the wear and tear, and as a result, increasing the engine's time on wing.

(c) The operating environment influences the engine's deterioration in primarily two ways: First, depending on where the aircraft is operated, the engine is subjected to particles of salt, sand, dust and/or pollution. This increases the surface roughness of the airfoils and changes their shape due to erosion, which decreases the engine efficiency as it distorts the blade aerodynamics (Diakunchak, 1992; Chen & Sun, 2018). In this case, the control system of the fouled engine has to increase the fuel flow to meet the required thrust during the flight, therefore increasing the EGT, which may further speed up the life consumption of the hot section components (Igie, Diez-Gonzalez, Giraud, & Minervino, 2016). The second environmental effect is caused by the Outside Air Temperature (OAT) and is illustrated in Fig. 2. As the OAT increases, so does the

[1] Based on the officially published list prices by Airbus (e.g. $101M for the A320ceo) (Airbus, 2018) and estimated purchasing cost for selected engine variants (e.g. 2×$10M for the CFM56-5B) (Deagel, 2020).

EGT for a given thrust setting, since the engine power management systems are typically designed to maintain a constant thrust. At a manufacturer defined corner temperature, the control system keeps the EGT constant by reducing the thrust. This again influences the engine's wear and tear behavior as described in item (b) of this list[2].

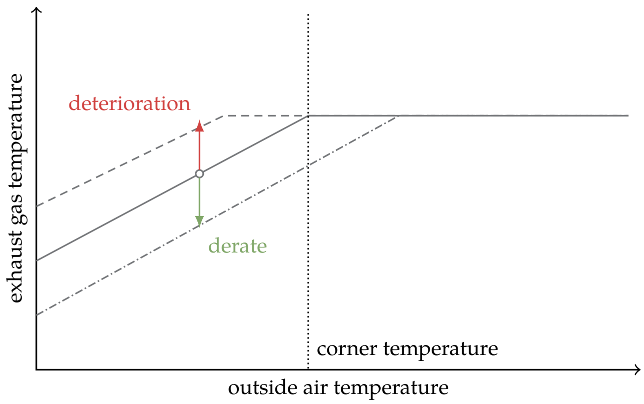

Figure 2. Illustration of takeoff exhaust gas temperature vs. outside air temperature with the effects of deterioration and derate.

The EGT is an indicator of the engine's current health as it increases with its age and level of deterioration. Engine manufacturers specify an engine specific upper EGT limit (EGT_{max}), which must not be exceeded. This temperature limit is usually defined by the material technology at the inlet of the High Pressure Turbine (HPT), since this part of the engine will experience the most severe combination of high gas temperatures and high dynamic loads (Hanumanthan, 2009). The difference between the peak EGT during take-off and EGT_{max} is defined as the Exhaust Gas Temperature margin (EGTM). Especially for engines operated on low EFH/EFC ratios, the depletion of EGTM is often the dominant reason for an ESV (Ackert, 2011; Aircraft Commerce, 2007, 2006).

2.2.2. Engine Maintenance

Engine maintenance practices are preventive in nature and combine a condition based and a hard time based replacement approach. For the former, operational parameters such as the rotor speed, oil consumption, vibration, fuel flow and the EGT are constantly monitored. The hard time based replacement strategy primarily deals with Life Limited Parts (LLPs) (Ackert, 2011). These are certain parts of the engine that cannot be contained if they fail and therefore have to be exchanged beforehand, which is specified by a maximum number of flight cycles. These LLPs typically include disks, seals, spools, and shafts (Ackert, 2011).

[2]For more information on the relationship between OAT, thrust control, EGT margin and derate, consider (Ackert, 2015).

Compared to the Remaining Useful Lifes (RULs) of LLPs, the consumption of EGTM is more complex in nature, as it not only depends on the number of performed flight cycles, but is additionally influenced by the factors mentioned in Section 2.2.1. Its restoration also allows multiple maintenance measures, e.g. a replacement of degraded core components, a permanent downrating or temporal derating to reduce its nominal thrust, or an EW as a ground-based, on-wing maintenance alternative. In the latter, water and cleansing additives are pumped into the engine's intake, which removes accumulated dirt from the airfoil surfaces of the compressor and turbine. EW can lead to an EGTM restoration of up to $15°C$ (Ackert, 2011; Hutter, 2006), which in turn reduces fuel consumption up to 1.2% (Hutter, 2006).

The overall economic effectiveness of on-wing engine maintenance tasks depends on multiple factors. Apart from their cost, these include:

- The timing of an EW, as dirt has to be accumulated first, before it can be washed away.
- The sensitivity of the engine's Specific Fuel Consumption (SFC) on the EGTM, as it determines the resulting fuel burn savings. This is cited to be within the range of 0.07 (Hutter, 2006; Krause, 2011) to $0.1\,\%$ (Justin & Mavris, 2015) of SFC increase per $°C$ of EGTM loss.
- The current and forecasted fuel price that determines the potential fuel cost savings of an EW can bring.
- The value of more time on wing, since EW is also able to delay the next ESV visit, if it is triggered by an EGTM consumption.

These factors also apply in part to ESVs, as they also restore EGTM and improve aircraft fuel efficiency. In general, two different workscopes are performed during an ESV: The performance level workscope and the full overhaul. In the former, the engine is partly disassembled and airfoils, guide vanes, seals, and shrouds are inspected and repaired or replaced if required. This can restore about $60\,\%$ of the EGTM. This recovery percentage can reach $80\,\%$ after a full overhaul in which the engine is completely disassembled and each part is thoroughly inspected and repaired/replaced as needed. (Aircraft Commerce, 2006, 2007)

These strong relationships between the EGTM, EWs, ESVs, and fuel efficiency provide a suitable use case for demonstrating the fleet expansion of LYFE.

2.3. Current Research on Engine Wash

Most studies on EWs have drawn their system boundary around the engine and consider only the direct improvements that result from a wash. Schneider et al. (2010) performed a holistic analysis of on-wing washing to investigate the impact on gas turbine performance improvement (Schneider, Demircioglu Bussjaeger, Franco, & Therkorn, 2010). Roupa et al.

(2013) took a closer look at the cleaning effectiveness of on-wing washing to remove contamination to better understand the direct impact of EW on the engine (Roupa, Pilidis, Allison, & Lambart, 2013). Igie (2017) provides a comprehensive overview of the compressor fouling effect and compressor wash for both stationary and jet engines (Igie, 2017). From these studies, it has been shown that EW performance and the optimum wash interval depend on a number of factors, including EGTM, number of flight cycles, physical condition of the compressor, etc.

Some studies address the individual health status of the engine and the associated uncertainty of when to perform an ESV to maximize ToW but not exceed the engine load limits. Based on the findings of EW and the PHM approach to engine health monitoring, these studies address individual detection of when EW is necessary/beneficial. Skaf et al. (2013) applied change detection to detect on-wing washing events and developed a prognostic algorithm to use the EW data to estimate the RUL of gas turbines (Skaf, Zaidan, Harrison, & Mills, 2013). The time when an EW is performed, however, is only calculated on the basis of past data. Possible effects in the future are not taken into account.

In addition, the influence of EWs on flight operations and the resulting economic effects were also studied. Giesecke et al. (2012) studied the benefits of EWs on a short-range aircraft engine for different wash intervals and developed a techno-economic model for this purpose (Giesecke, Igie, Pilidis, Ramsden, & Lambart, 2012). Chen and Sun (2018) proposed a Monte Carlo simulation-based method to estimate the achieved improvement in engine performance and calculate the potential fuel burn savings of an aircraft fleet by applying EW (Chen & Sun, 2018). Long-term effects that build on these improvements, such as changes in maintenance and replacement cycles, are not considered. To conclude, the value of on-wing washing processes is often quantified on an insufficient setting, especially when environmental conditions or fleet effects are neglected.

3. Framework for Engine Fleet Assessment

The aim of this study is to more accurately capture the value of EW within the aircraft lifecycle. As mentioned earlier, several changes within LYFE are necessary to perform this study. As the selected aircraft fleet also influences the study results, this and other simulation assumptions are documented in this section. Predicting ESVs and dynamically triggering EW events is done through different prognostic algorithms, which are presented below.

3.1. Assessment Fleet Description

Within the framework of this study, we decided to simulate an A320 family fleet from Finnair, using the CFM56-5B engine as basic version. The fleet consist of three different aircraft types: A321, A320 and A319 and comprises a total of 23 aircraft[3] (Aircraft Commerce, 2007). All important information regarding this fleet are summarized in Table 1. The other data underlying the simulation were taken from the Piano-X database, a professional aircraft evaluation tool[4].

Table 1. Finnair Fleet Information from Cirium Fleet Analyzer and (Aircraft Commerce, 2007)

	A321	**A320**	**A319**
Number in Fleet	6	10	7
MTOW [lbs]	162,040	196,244	149,914
Number of Seats	209	174	144
Engine Variant	-5B3	-5B4	-5B6
Thrust [lbs]	32,000	27,000	23,500
Dry Weight [lbs]	5,250	5,250	5,250
Initial EGTM [$^\circ C$]	66	109	145
LLP EFC Limit			
HPT	14,300	17,600	17,600
HPC	17,200	18,200	18,200
fan	20,000	25,000	25,000
LPT	25,000	25,000	25,000

Each aircraft type has its own flight schedule that is created based on the annual flight plan from one exemplary aircraft of each type[5], shown in Figure 3. The number of flights and the average EFH/EFC ratio per flight schedule are summarized in Table 2.

Table 2. Flight Schedule Information

	A321	**A320**	**A319**
Number of Flights	1746	1546	1813
Number of individual Routes	96	126	136
Average Route Length [km]	873	1090	906
Average EFH/EFC Ratio	1.6	1.9	1.7

Within the scope of the simulation, each aircraft has a service life of 25 years. An article from Aircraft Commerce serves as the basis for the airframe maintenance schedule (Aircraft Commerce, 2006). This maintenance plan is divided into line and base maintenance. The line maintenance consists of regular transit, pre-flight, daily and weekly checks. Balanced A-checks and a repeating eight-check cycle for the heavier C-checks make up the base maintenance. This plan also takes heavy component maintenance and recurring charges

[3] extracted from Cirium Fleet Analyzer on 10/03/2021
[4] See https://www.lissys.uk/PianoX.html, last accessed on 12/05/2021
[5] A321: MSN 1185, Tailsign OH-LZC. A320: MSN 1712, Tailsign OH-LXF. A319: MSN 1364, Tailsign OH-LVI. Flight schedules from 01/01/2019 to 31/12/2019 extracted from flightradar24.com on 01/09/2020 and 22/03/2021

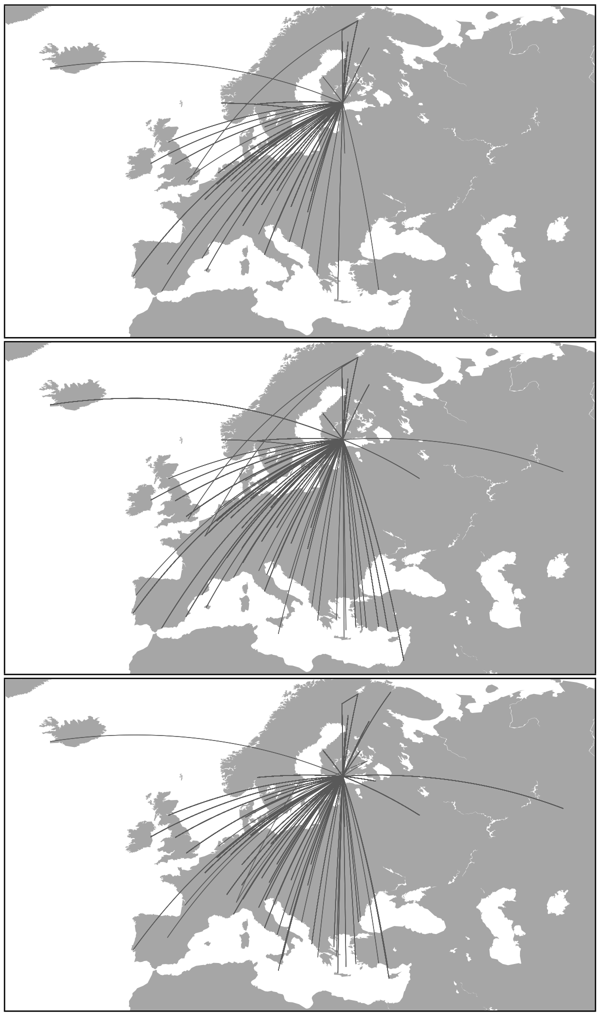

Figure 3. Route Network of OH-LZC (A321 - top), OH-LXF (A320 - mid) and OH-LVI (A319 - bottom) in 2019 extracted from `flightradar24.com`

for rotables into account. Since no information on EW cost are available, we assume them to be US$ 3000 per engine per wash.

Each engine has individual wear and tear curves which were created based on interviews of Maintenance Repair and Overhaul (MRO) providers from (Aircraft Commerce, 2007). The progression hereby is not linear, but can be divided into two areas with different wear behavior. The first area represents the initial rates of loss, where a first increase of the EGT can be identified. With a longer running time the rate of loss decreases and then changes into a linear progression, which represents the second, mature area. The turnover point is different for each engine and lies by 7200 FC for the -5B3 and by 3000 FC for the -5B4 and -5B6. These deterioration curves are composed of the curve for wear and tear and the curve for dirt. The correlation of EGT increase to SFC in this case is assumed to be 0.1%. Figure 4 shows the three Exhaust Gas

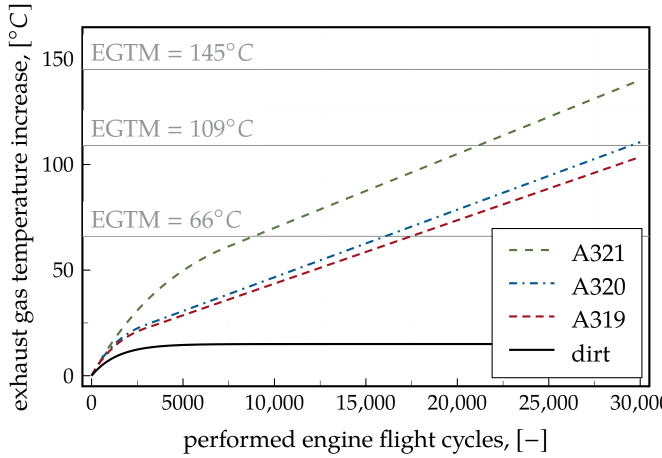

Figure 4. Modeled EGTi of the CFM56-5B engine types for the A321, A320 and A319 (Aircraft Commerce, 2007)

Temperature increase (EGTi) curves and the curve for the dirt accumulation, which is modeled without any available data and is solely based on an educated guess. Note that only the dirt-induced EGTi is removed by EWs and the wear-induced EGTi remains unaffected. The corresponding equations are shown in Table 3.

Table 3. Corresponding Equations for Figure 4

Aircraft	**Initial Rate of Loss**	**Mature Rate of Loss**
A321	$79.4 \cdot (1 - 0.9998^{EFC})$	$0.0035 \cdot EFC + 35$
A320	$30 \cdot (1 - 0.99945^{EFC})$	$0.0032 \cdot EFC + 14.62$
A319	$28 \cdot (1 - 0.99945^{EFC})$	$0.003 \cdot EFC + 13.6$
dirt	$15 \cdot (1 - 0.9993^{EFC})$	

3.2. Extensions in LYFE

In the existing version of LYFE, an ESV is triggered based on a FC or FH interval passed over to LYFE from the input data. To make this interval more specific, the ability to monitor the engines health and the related parameters are added. In addition to that, an aircraft does not always operate with the same engine (on which assumption LYFE is based until now). The lifetime of an engine and an aircraft differ and both maintenance schedules are independent. With the performed framework modification, the aircraft and the engine are two different objects that can communicate with each other. Due to the separation, it is possible that the life of an aircraft exceeds the life of an engine. To map this resale of the used engine, we have used a simplified and time dependent model for the loss of engine value.

3.2.1. Engine Health Monitoring During Simulation

Due to the condition based nature, the engine maintenance is considered separately from the FH/FC/time triggered schedule. Each ESV will be triggered individually based on either the EGTM or RUL of the LLPs. In order to predict the timing of maintenance events, different information regarding the engines health like the thrust, the initial EGTM and the LLP limits of each engine (Aircraft Commerce, 2007) are necessary. The values used for the simulation can also be found in Table 1. In addition, EGTM recovery after an ESV was performed under the assumption that a core restoration would achieve 60% and a full overhaul would achieve 80% of the original margin, as described in Section 2.2.2.

To trigger the ESV of an aircraft more precise, the EGTM and the LLP of this engine need to be monitored during the whole lifecycle simulation. This is because the discrete ESVs are triggered if either the EGTM approaches zero or the RUL of one of the LLPs falls below 1% of the LLP margin. Both mechanisms are illustrated in Figure 5.

Within this research we started to monitor the EGTi according to the simplified EFC dependent model. As stated in Section 2.2.1, the OAT also has an influence on the EGT. Since no data of the variation of the EGTi due to the OAT is available for the CFM56-5B engine, we assume that the EGTi variation of the CFM56-7B, which is around $1.5 - 2.0°C/1000EFC$, is roughly equivalent to the values of the CFM56-5B (Aircraft Commerce, 2008). We also assume that this variation is only due to the changing OAT in the range of $-30°C$ and $30°C$ and has a linear progression. Consolidated, the real EGTi varies by $0.000025°C$ EGTi per $1°C$ of OAT.

$$EGTi_{real} = 0.000025 \cdot OAT + EGTi \quad (2)$$

Within LYFE, information, such as location, time zone, local curfews, as well as weather information which include the monthly mean OAT at local day- and night-time, about approximately 6000 different airports worldwide are available in LYFE's airport database. For this, publicly available climate data from 2017 to 2019 were analyzed and processed[6].

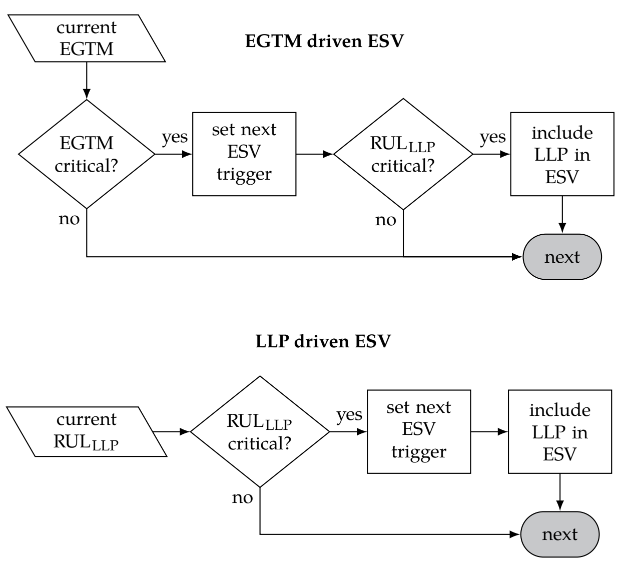

Figure 5. Implemented mechanisms of EGTM or LLP driven ESV (Pohya et al., 2021)

3.2.2. Separation of Engine and Aircraft

To map the interaction between the engine and the aircraft, both are represented individually as objects. They can act independently in an environment, perceive certain states and state changes, and make independent decisions based on these changes. They are also able to proactively pursue a goal and have a social ability, meaning they are able to communicate with each other (Wooldridge & Jennings, 1995).

In detail, this means that the engine object constantly monitors its own health. For this purpose, it counts the flown EFC and monitors the RUL of the LLPs per flight. It also recalculates the current EGTM after each flight. Based on these observations, it decides when an ESV must occur, which is the case, if the RUL of the LLPs or the EGTM reaches zero. When an engine goes into an ESV its status changes to 'in ESV'. This status change is important because it can be queried by the aircraft object. After the ESV is complete, the engine is operational again and is reinstalled on the aircraft. Now the status changes back to 'operating'. In the meantime, while the main engine is in an ESV, the aircraft needs a spare engine to continue operating. To find an available spare engine, the aircraft contacts the spare engines pool and requests their status. If this status is 'in ESV' or 'operating', the engine is not available, if the status is 'free' it can be used. If a free spare engine is found, this engine is operated on the aircraft for the time the main engine is in an ESV. After the ESV of the main engine, the engines swap again (see Figure 6).

3.2.3. Engine Resale Price Calculation

The lifetime of the engine does not correspond to that of the aircraft. Each engine has only a certain number of ESVs before the cost exceed the procurement cost for a new engine (Nelson, 1977). This statement was also confirmed by an MRO provider: Many engines even have a maximum number of ESVs set by the manufacturer. In our case, we assume that the CFM56-5B engine will go through three ESVs (Aircraft Commerce, 2008, 2007).

When this usage limitation of the engine is reached the engine will go out of service and will be sold and reused as e.g.

[6]See ECMWF. URL: `https://cds.climate.copernicus.eu`, last accessed on 11/2020/04. For further information see (Hersbach et al., 2018)

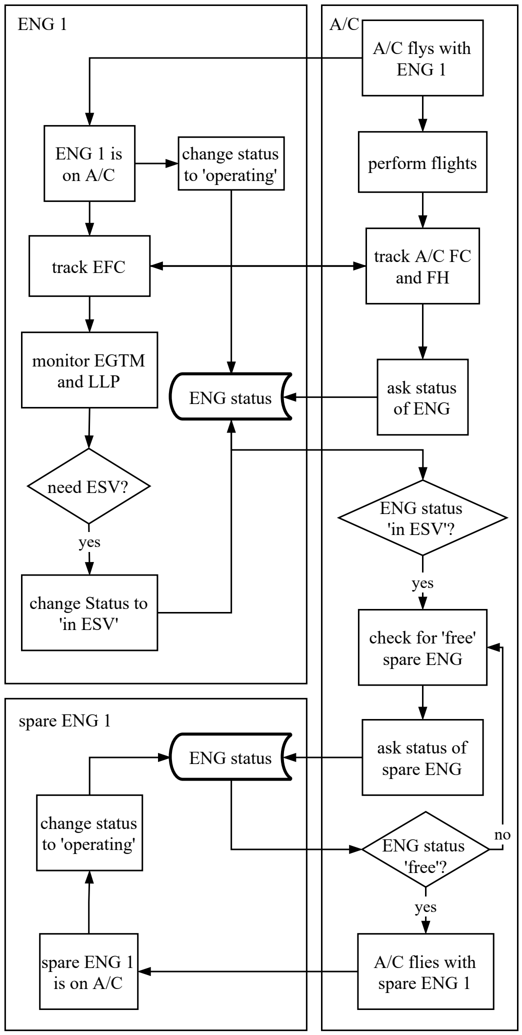

Figure 6. Implemented interaction between aircraft and engine

spare parts (Howe, 2011; Seemann, Langhans, Schilling, & Gollnick, 2010). In order to get a resale price of the engine and since no data on the Current Market Values (CMVs) of engines are available, we assume that the loss of the engine's resale value is equal to that of the aircraft itself.

Aircraft Commerce collected the CMVs of aircraft of the A320 family from 1988 until 2005 in year 2005. Based on these value losses the following relationship between CMV, years in service y and purchase price P was determined (Aircraft Commerce, 2006).

$$CMV = P \cdot (0.1115 \cdot y^{\,0.6386}) \quad (3)$$

The purchase prices (in Euro) of the engines used within this study are calculated with the following formula (Langhans, 2013), which only takes the dry weight of the engine (Safran Aircraft Engines, 2021) (W_{dry}, see Table 1) as an input parameter:

$$P = (2.941 + 0.2603 \cdot W_{dry} + 0.04765 \cdot W_{dry}^2) \cdot 10^6 \quad (4)$$

3.3. Prognostic Strategies for Engine Wash Usage

For the analysis of on-wing washing, we compare a reference scenario in which no EWs are performed with different prognostic strategies. Within these PHM strategies, the EW events are triggered according to different optimization strategies, which differ in their prognostic horizon and considered cost:

(a) Within the first strategy (fuel strategy) the on-wing washing events are triggered, if the fuel burn savings due to an EW are higher than its cost. The prognostic horizon for the predicted fuel burn of this algorithm lies between now and the next determined ESV.

(b) The aim of the second approach (ToW strategy) is to consider not only fuel consumption and the resulting fuel savings, but also a possible longer ToW of the engine caused by EWs. If the ToW of the engine can be extended by EW, the EW cost per FC will be less than if no ToW reduction can be achieved. This normalization of the costs allows a value to be assigned to the longer ToW. For this reason, an EW is performed whenever the fuel savings per FC exceed the cost per FC of the EW.

(c) The third approach (LCC strategy) builds on the second and differs only in the prognostic horizon considered, which is extended to the end of the engine's life. It thus includes the cost of all ESVs until the engine's disposal while forecasting the future EGT and with that fuel consumption.

In Figure 7 the different prognostic horizons are shown for two possible cases: the first case predicts the EGT curve if an EW would be done at 4700 EFC while the second case assumes that an EW is performed at 15000 EFC. If the next ESV is triggered by the EGTM, then a longer ToW due to

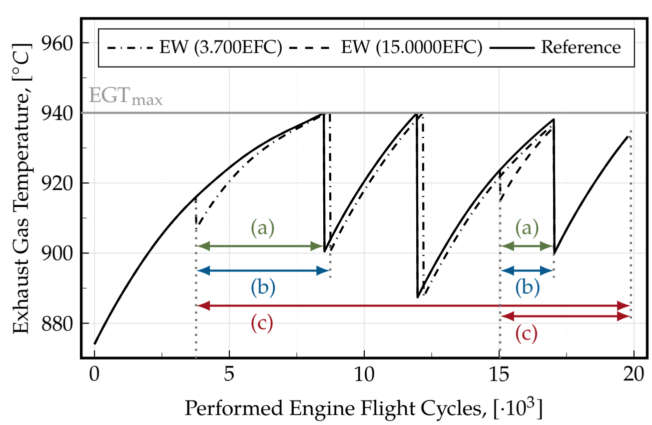

Figure 7. Different prognostic horizons of the fuel strategy (a), the ToW strategy (b) and the LCC strategy (c)

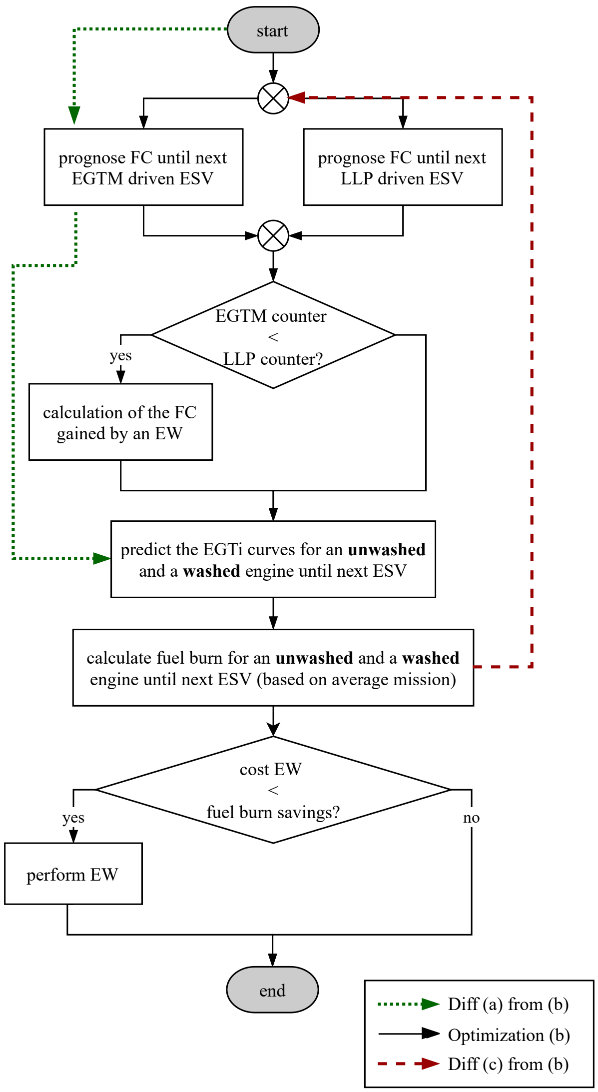

Figure 8. Fuel algorithm (a), ToW algorithm (b) and LCC algorithm (c) to trigger the engine wash events

on-wing washing is possible. If the shop visit is triggered by an LLP limit, no ToW extension is possible.

Figure 8 shows the sequence of the three different strategies and the respective differences. Depending on the algorithm, different cost per FC are considered for different prognostic horizons and compared at the end. If the total cost of performing an EW are lower than the cost of not performing an EW the due date of the next EW is set to the current simulation time.

4. Simulation Analysis and Results

The analysis of this paper and its results are divided into two parts. The reference case (i.e. without any EW measures) is examined in the first part, whereas the second part looks at on-wing washing procedures in more detail, discussing the influence of the different prognostic strategies.

4.1. Reference Case

To recall, the reference case does not consider any on-wing engine cleaning procedures and serves as a baseline for later comparison with the prognostic strategies.

Figure 9 shows the NPV of the total fleet (left axis, black line) as well as for each individual aircraft (right axis) for the simulation period. Here, all red lines (dashed) show the NPV trajectories of the six A321 aircraft, while the green lines (dash dotted) show those of the ten A320 aircraft and the blue lines (dotted) show those of the seven A319 aircraft. The simulation period ranges from 1995 to 2029 due to the different entry into service dates and the associated different end-of-life dates of the aircraft. Within this figure three typical periods of the aircraft NPV progression can be seen: (a) During the first years the NPV has a negative trend, which represents the non-operating years after order in which the advance payments are made. (b) With the turn at the most negative point the operating phase starts. Here the airline starts to make revenues with the aircraft but the NPV is still negative. (c) The third phase starts with the break even point, where the NPV becomes positive and the aircraft brings an added value to the airline. All A321 and A320 aircraft reach this point after around 7-10 years of operation, while the A319 aircraft either reach this point at the end of their service life or do not reach it at all. The reason for this lies in the airline's deployment strategy, that was assumed in this study. All NPV progressions consolidated generate the NPV development of the total fleet (black solid line), ending in a positive NPV in year 2029.

Furthermore, it can be seen that the NPV of the aircraft that have an early Entry into Service (EiS) end up being higher than that of the aircraft with a later EiS. This effect is due to the discounting of the individual cash flows. Further assumptions regarding the assessment, such as the fuel price scenario, can be found within these publications (Pohya et al., 2020;

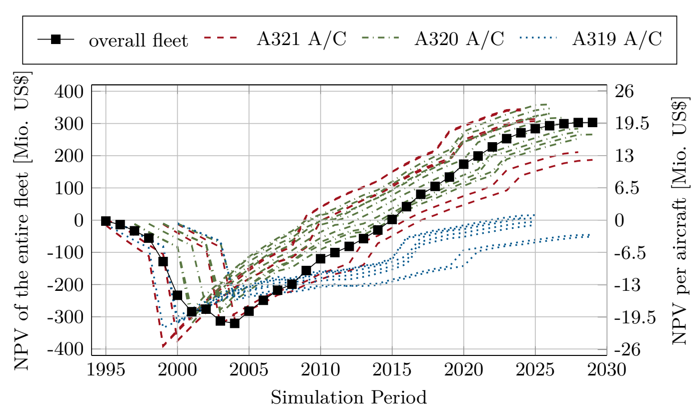

Figure 9. Fleet and aircraft NPV of the simulation period

Pohya & Wicke, 2019). Table 4 summarizes the average fuel cost, DMC and LCC for the different aircraft types and for the whole fleet. It is noticeable that the fuel cost of the A320 are about 35% higher than those of the A319 and A321. This difference is due to two effects: First, the average flight length of the A320 is 20% higher than that of the A319 and 25% higher than that of the A321 (compare Table 2). A second reason is the difference in average fuel cost per FC. The A320 aircraft have later EiS dates compared to the other aircraft, so the average fuel cost per FC for these aircraft are higher than that of the others, due to rising fuel prices. When considering these results, it must be taken into account that only delta observations provide meaningful results. This presentation of specific results is more for interpretation and order of magnitude.

Table 4. Summarized average cost of the reference case

	Fuel Cost $[\$/FC]$	**DMC** $[\$/FC]$	**LCC** $[\$/FC]$
A321	1007	874	6282
A320	1388	820	6129
A319	1042	769	5096
total	1184	818	5854

As described in Figure 6 each aircraft has its main engines, while the spare engines are available for all aircraft. Figure 10 shows a part of the lifecycle of three aircraft from the beginning of 1999 until the middle of 2005. Here it can be seen, that since the ESVs from OH-LZB and OH-LZC are overlapping they cannot use the same spare engine while the tail-signs OH-LZB and OH-LZA have no overlaps in their ESV schedule and use the same spare engines.

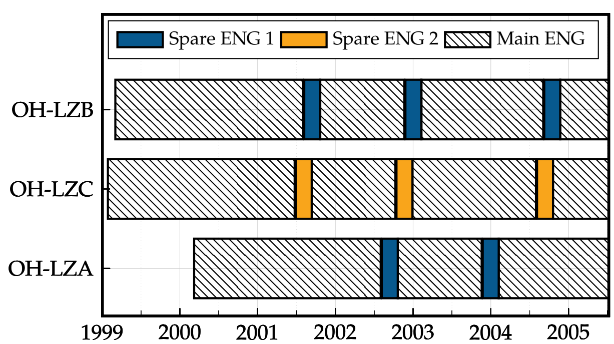

Figure 10. Lifecycle excerpt to show the use of spare engines

4.2. Prognostic Strategies

While the ToW of the A321 engines vary if EWs are carried out, on-wing washing has no influence on the ToW of the A319 and A320 engines. The reason for this is that in this study case all ESVs of the A320 and A319 engines are triggered by LLPs while the first two ESVs of the A321 are triggered by the EGTM limit. Since an EW can only restore EGTM, but does not change the limit of the LLPs, EWs only have a positive effect on the ToW if the actual ESV would take place due to the EGTM. On the basis of this, the A320 and A319 will not be further analyzed regarding a possible ToW extension due to on-wing washing, while the effects of all three prognostic strategies on the A321 engines are shown in Figure 11.

In this figure the EGT is plotted over the performed EFC for one engine operating on the A321 for (a) the fuel strategy, (b) the ToW strategy and (c) the LCC strategy in each case in comparison to the reference. Every time the EGT curve decreases vertically the engine was subjected to an ESV. Here it can be seen, that if only the improvement of fuel cost is considered in the prognostic strategy, almost no ToW improvement is achieved (top figure). If, on the other hand, the extension of the ToW is explicitly taken into account in strategy (b) (middle figure), then an average ToW extension of 2240 FC can be de-

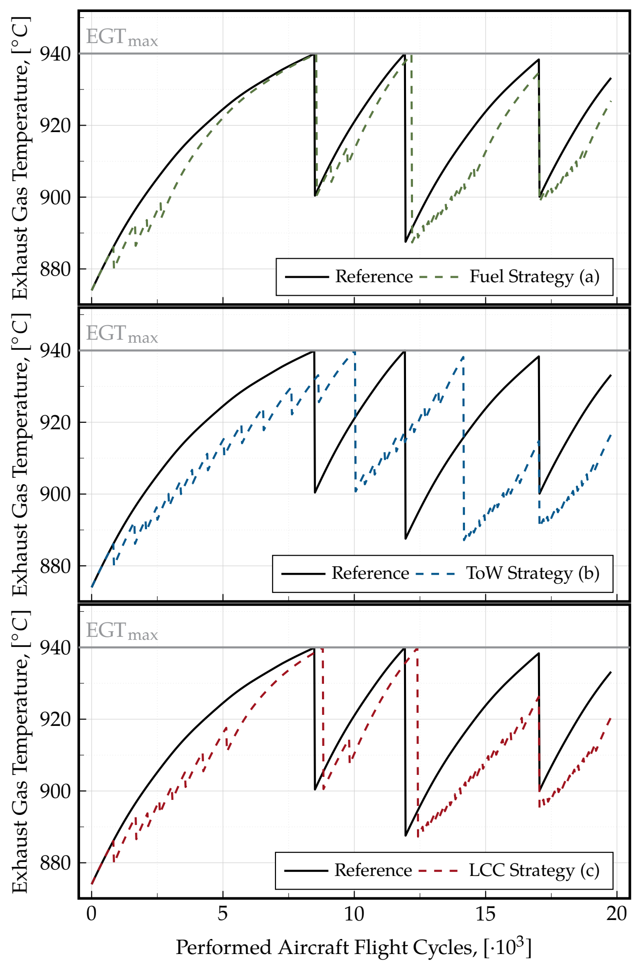

Figure 11. EGT developments of (a) the fuel strategy, (b) the ToW strategy and (c) the LCC strategy compared to the reference case

Table 5. Results of (a) the fuel strategy, (b) the ToW strategy and (c) the LCC strategy compared to the reference case

	Δ Fuel Cost [%]			**Δ DMC [%]**			**Δ LCC [‰]**			**av EW per year**		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
A321	-0.6	-1.2	-0.7	0.9	-0.7	1.8	-0.3	-2.5	0.6	4.3	8.3	6.6
A320	-1.7	-1.9	-1.9	5.7	6.2	6.1	-0.1	-0.2	-0.6	13.1	14.3	14.3
A319	-0.8	-0.8	-0.7	1.1	1.7	1.7	-1.0	-0.5	-0.3	3.4	4.6	4.6
total	-1.1	-1.4	-1.2	3.1	3.0	3.6	-0.4	-0.9	-0.2	6.9	9.1	8.5

tected for the period up to the first ESV. The ToW between the first and the second ESV remains equal and the ToW between the second and the third ESV is decreased by an average of 2220 FC which is due to the fact that in both cases the limit of one LLP is reached. Due to the LLP limits, the total EFC cannot be increased over the entire lifecycle of the engines used within this study even if on-wing washing is performed.

The different forecast horizons of strategy (b) and (c) have a different impact on the number of EWs and on the extension of the ToW. Since no extension of the service time can be achieved, cost savings within the LCC strategy (c) only occur if more fuel is saved than cost are added by an EW, which is why the results of strategy (c) differ only minimally from the results of strategy (a). Due to the reason, that the lifetime of the engines cannot be extended through EWs, the number of required engines within the fleet remains constant, i.e. EWs are not capable of reducing the number of main and spare engines within this study case.

The figure also shows that at the beginning of the engine's lifetime, the intervals between EWs are larger than towards the end of the lifetime. This aspect is due to the increasing fuel price over time. If the fuel cost are higher, even a smaller fuel saving is sufficient to compensate for the EW cost. In addition, it can be seen that the number of EW decreases the closer an ESV gets, which is also due to the forecast horizon and its variability. Depending on the length of the forecast period, the possible fuel saving amount becomes smaller as the end of the forecast period approaches, which is why no more savings can be achieved after a certain point. The length of the forecast period is the reason for the small differences in the results between strategy (a) and (c). Since in strategy (b) an extension of the ToW is considered and can be achieved, the observation period is variable and the implementation of the EW is still profitable quite close to an ESV.

In Table 5 the average Δ fuel cost, Δ DMC, Δ LCC and the average number of EWs per year for the A321, A320 and A319 aircraft as well as for the total fleet for all three strategies are shown. In each case, the costs per FC serve as the basis for the delta analysis. As intended by the algorithms, fuel cost savings can be detected for all three strategies, with higher savings for the A321 aircraft in strategy (b), while the A320 and A319 savings remain about the same for all strategies. This effect is due to the number of EWs performed per aircraft and year. In strategy (b), the A321 performs about twice as many EWs per year as in strategy (a). These differences between the A321 and the A320 and A319 are due to the fact that an extension of ToW is possible for the A321 but not for the A320 and A319, so the differences between the algorithms are mainly reflected in the A321 results. The fuel cost of the A321 also show that there is a significant difference between strategy (b) and (c). Since the prognostic horizon of strategy (c) is equal to the service life and no extension of the engine life is possible, these results are more comparable to the results of strategy (a) (see also Figure 11).

As expected, DMC increase as more cost are incurred by executing EWs, with the exception of the DMC of the A321 in strategy (b), where DMC decrease. This is due to the fact that an aircraft is operated for exactly 25 years. The lifetime of the last used engine to operate the aircraft does not end with the lifetime of the aircraft and still requires an ESV in the reference case shortly before the aircraft goes out of service; by extending the ToW within the strategy (b), this ESV is shifted so that it would occur outside of the simulated lifetime of the aircraft, resulting in lower cost. The LCC remain about the same for all strategies and aircraft.

In a comparison of the three aircraft types, it can be seen that the A320 performs significantly more EWs per year than the other two aircraft types. This is associated with higher fuel cost savings and an increase in DMC compared with the reference. Table 4 shows that the A320 has significantly higher fuel cost per FC than the other two aircraft types, which is mainly due to different average flight lengths of the individual aircraft types, as already described in Section 4.1. With higher fuel cost comes a higher fuel cost savings potential, which is why more EW can be conducted without increasing LCC.

In conclusion, this study gives some insights regarding on-wing washing of engines:

(a) A possible longer time on wing of the engine can only be achieved, if the ESVs are triggered due to an exhausted EGTM, as it is the case for the A321 engines. Here an extension of an average of 2240 FC is achieved until the first ESV. If the limit of the LLP is reached an EW can only reduce the fuel burn, which is the case for the A320 and A319 engines.

(b) Within the possible prognostic strategies, a longer time on wing is not achieved if the EW events are selected based only on potential fuel cost savings. If, on the other hand, an EW is performed when there is not only a fuel cost advantage but also a ToW advantage due to cost saving of omitted ESV, the ToW can be extended, whereby the LLP limits may also play a central limiting role.

(c) The number of main and spare engines required per fleet cannot be reduced by on-wing washing in this use case.

Due to some assumptions on which the study of this paper is based, the results must be interpreted with care. Firstly, a rather old engine model was used for these investigations, as insufficient information is available for newer models. Secondly, the model used for the accumulation of dirt is based exclusively on assumptions and engineering guesses. For future work, it would be interesting to analyze different dirt accumulation models and their affect on the engine health in combination with EW.

5. Summary and Outlook

Within this paper three prognostic strategies to perform on-wing washing were presented and analyzed with respect to economic efficiency. All three strategies pursue the goal of carrying out EW as efficiently as possible, whereby different aspects considered distinguish the strategies from one another. On the one hand, a possible fuel cost reduction through EW is included. In addition, a possible extension of the ToW is taken into account, and the prognostic horizon is varied. To perform these studies some adaptions were made to the lifecycle cash flow environment LYFE, a discrete event simulation environment developed by DLR. These changes include the separation of the aircraft and the engines as individual objects and a prognostics and health management approach to monitor the engine. As part of a mixed engine maintenance strategy of condition-based overhaul and hard-timed replacement, Finnair's A320 family fleet operating with the CFM56-5B engine was investigated. Correlations between engine condition (expressed in EGT and distinguished between dirt- and wear-related degradation), its influence on fuel burn, partial EGT recovery capabilities of EWs and ESVs, and RUL of LLPs were included in the evaluation. The results show, that an improvement of the ToW of the engine is possible due to on-wing washing procedures. To investigate this behavior in more detail, future work should consider using a newer engine model that is more designed for EW application. In addition, a more detailed dirt accumulation model should be investigated.

Acknowledgment

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Nomenclature

CER	Cost Estimation Relationship
CMV	Current Market Value
DMC	Direct Maintenance Cost
DOC	Direct Operating Cost
EFC	Engine Flight Cycle
EFH	Engine Flight Hour
EGT	Exhaust Gas Temperature
EGTi	Exhaust Gas Temperature increase
EGTM	Exhaust Gas Temperature margin
EiS	Entry into Service
ESV	Engine Shop Visit
EW	Engine Wash
FC	Flight Cycle
FH	Flight Hour
HPT	High Pressure Turbine
LCC	Lifecycle Cost
LLP	Life Limited Part
LYFE	Lifecycle Cash Flow Environment
MRO	Maintenance Repair and Overhaul
NPV	Net Present Value
OAT	Outside Air Temperature
OoI	Object of Interest
PHM	Prognostics and Health Management
RUL	Remaining Useful Life
SFC	Specific Fuel Consumption
ToW	Time on Wing
WLCC	Whole Lifecycle Cost

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BIOGRAPHIES

Jennifer Wehrspohn is a scientist at the Institute of Maintenance, Repair and Overhaul within the German Aerospace Center (DLR). She currently pursues her Ph.D. as a member of the product lifecycle management group. Her research interest lies in the economic evaluation and operational impact assessment of novel maintenance technologies for hybrid electric aircraft. To pursue this goal, she is involved in evaluating existing maintenance technologies at fleet level in order to adapt these methodologies for novel technologies in the long term. Before joining DLR, she earned a Master's Degree in Business Administration and Mechanical Engineering at RWTH Aachen University in 2020.

Ahmad Ali Pohya is a scientist at the Institute of Maintenance, Repair and Overhaul within the DLR. He currently pursues his Ph.D. as a member of the product lifecycle management group at the RWTH Aachen University. Research topics include lifecycle modeling and integrated uncertainty quantification in the context of aeronautical techno-economic evaluation. He is also the main developer of the used software environment LYFE. Before joining DLR, he received his Masters' degree in Product Development in Mechanical Engineering in 2017 from Hamburg University of Technology.

Dr. Kai Wicke is the head of the department for product lifecycle management at the Institute of Maintenance, Repair and Overhaul within DLR. He received his diploma degree in Aeronautical and Aerospace Engineering from the Technical University of Berlin in 2009 and holds a Ph.D. from the Hamburg University of Technology. His research focuses on the assessment of aerodynamic technologies on air transportation system level with respect to economic and ecological impacts. Due to his deeply contextual work contribution and assignment as (sub-)coordinator in internal, national and European projects such as LamAiR, SLED, IATA TERESA, ECHO, etc., he has gathered long-term experience within the fields of aircraft lifecycle cost-benefit modeling and assessment, technology assessment as well as systems analysis. He is a member of the AIAA society.