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IMPACT OF INSECT CONTAMINATION ON OPERATIONAL AND ECONOMIC EFFECTIVENESS OF AIRCRAFT WITH NATURAL LAMINAR FLOW TECHNOLOGY

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Abstract

The objective of this paper is to investigate the effect of insect contamination on operational and economic effectiveness of an aircraft with natural laminar flow wings designed by DLR. It is intended to show how insect debris located close to the wing leading edge influence fuel consumption on single missions as well as economic metrics like net present value. The focus will be on short-to-medium haul operations, i.e. aircraft similar to current state-of-the-art 150 passenger seated aircraft. During the analysis process tools for aircraft design, mission simulation and computation, insect contamination as well as life-cycle cost assessment will be used. The overall goal is to provide aircraft operators with a better understanding of the operational behavior of natural laminar flow aircraft under realistic operational boundary conditions and related economic implications.

1 Introduction

The minimization of aircraft operating cost is a major objective of today's airlines in order to increase profit and competitiveness. Due to increasing fuel prices over the last decades, fuel burn related cost has become one of the primary cost elements. Besides the economic pressure, airlines and aircraft manufacturers are pushed towards more environmentally friendly aircraft. Considering the high growth rates of air travel and the associated growing influence of aircraft operations on anthropogenic carbon dioxide emissions, the demand for a more environmentally responsible behavior of airlines will arise. The economical and environmental goals in the Flightpath 2050 Vision for Aviation of the European Commission represent an action to solve these problems. These ambitious goals cannot be achieved by today's aircraft design philosophies and more radical changes and improvements are necessary for future aircraft.

Natural laminar flow (NLF) on transport aircraft is a promising technology that offers significant potential for increasing the fuel efficiency of future aircraft [1, 2]. Simultaneously, the climate impact of aircraft can be reduced since less emissions are produced. In addition, NLF is a prospective technology that could be integrated in a next generation short-to-medium range aircraft. As outlined in a number of studies, a fuel burn improvement in the order of 10-12% [3, 4, 5] is possible by generating laminar flow on an aircraft wing. However, the existing numbers are only valid for optimum boundary conditions like operation at design range. To prove an economic operation of such aircraft, realistic airline operational boundary conditions like environment, technical efforts, and operational aspects must be taken into account [6]. In common airline operations, in-service performance degradation will emerge from off-design conditions, like short haul operation as well as from the influence of operational disruptions to laminar flow. One of the main risks to the operational effectiveness of aircraft with laminar flow is wing leading edge contamination with insect debris during takeoff and landing [7, 8]. Insect debris can cause premature transition of the laminar boundary layer during cruise flight. This in turn reduces the laminar flow benefit and aircraft economic viability. Various papers deal with the impact of insect debris and the adverse effects on laminar flow (resulting in drag increase) as well as means of avoiding such contamination [7, 9]. However, detailed investigations on resulting fuel burn penalties, and maintenance effort including repercussions on the aircraft's economic viability have been omitted so far.

This paper presents an enhanced system analysis process to determine the impact of leading edge contamination with insect debris on fuel efficiency and economic net benefit of an aircraft designed for NLF. To account for variable operational boundary conditions (e. g. mission length, fuel price fluctuations or maintenance cost), different assessment scenarios are considered and analyzed for their impact on aircraft profitability.

1.1 Analysis Approach

The applied approach to analyze the derogating effect of insect contamination on operational and economic effectiveness of NLF aircraft is schematically shown in Fig. 1. Starting point for the assessment is the NLF aircraft design including an aerodynamic optimization performed by DLR Institute of Aerodynamics and Flow Technology [10, 11]. Resulting aerodynamic and engine performance data are used in the subsequent analysis framework to determine key performance indicators (KPIs) on various system levels. To assess effectiveness on the operational level, flight performance computations are carried out with data from the insect contamination simulation and the aircraft design. The KPI used to measure the operational effectiveness is the relative mission fuel change on single missions due to the operation of the NLF aircraft by an airline. Finally, the economic effectiveness is derived based on the results from previous analysis steps. For this purpose a life-cycle costing tool is applied.

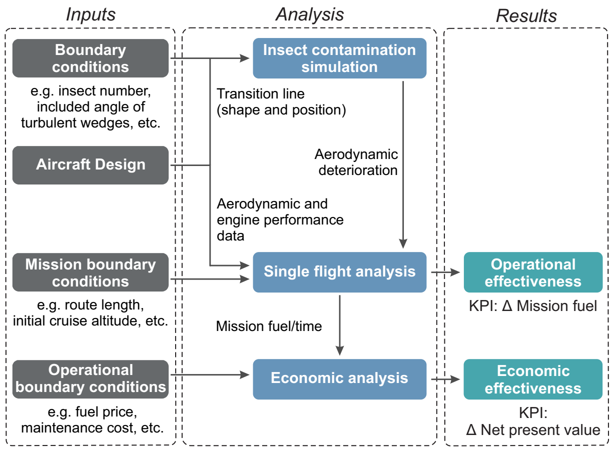

Fig. 1 Analysis approach.

2 NLF Aircraft Design

Conventional jet-powered transport aircraft feature backward swept wings to reduce wave drag and thus enable efficient transonic cruise flight. For typical leading edge sweep angles of 25° to 30° and Reynolds numbers of $20 \cdot 10^6$ and above, laminar-turbulent transition takes place close to the leading edge due to strong amplification of cross flow or attachment line instabilities [2, 12]. DLR's concept for a transonic NLF transport aircraft introduces a forward swept, tapered wing planform. Hereby, the leading edge sweep angle can be reduced to obtain conditions under which NLF becomes realizable [13]. Furthermore, the forward swept wing's shock sweep angle is large enough to maintain cruise Mach numbers comparable to those of today's short-to-medium range configurations. The combination of forward swept wing (FSW) and NLF promises gains in flight performance. The main disadvantage of FSWs is their tendency for aeroelastic divergence, causing additional weight for structural reinforcements [14]. Mitigating this problem, carbon fibre reinforced plastic (CFRP) can be used for aeroelastic tailoring to affect the deformational behavior of the wing systematically [15, 16]. At the same time, the

Table 1 Concept of operation and aircraft specifications.

Parameter	Value
Design range	4,815 km
Design Cruise Mach number	0.78
Design Payload	14,250 kg
Maximum Payload	19,250 kg
Seating	12 Business Class
	138 Economy Class
Take-off field length	7,000 ft
Landing field length	5,500 ft

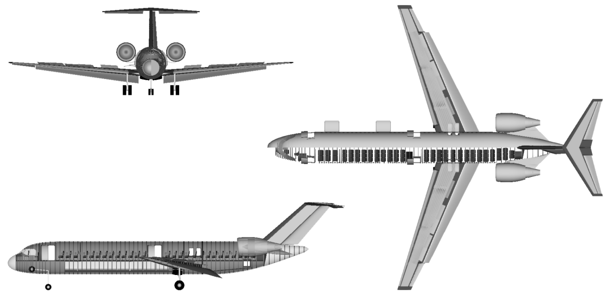

Fig. 2 DLR's concept for a FSW-NLF aircraft (designed with PrADO [20, 21]).

material properties of CFRP can be used to lessen the weight penalty and to obtain a high surface quality with respect to roughness and waviness [17, 18]. Detailed information about the preliminary aircraft design and additional studies are published in [10, 11].

The reference configuration represents an aircraft design similar to current state-of-the-art short-to-medium range aircraft with turbulent wing design. Both aircraft provide the same concept of operation (see Tab. 1). As illustrated in Fig. 2 the chosen design of the FSW-NLF aircraft features a T-tail and rear-mounted engines in order to create a clean wing with optimum laminar flow conditions. Due to an appropriate wing section design NLF is maintained over the forward part of the upper and lower wing. In order to consider NLF in early aircraft design stages, a simplified laminar-turbulent transition model is implemented in the design process, as described in [10, 19]. In the outer wing area the maximum transition location is about 55 % of local wing chord length. Thereby, the lift-to-drag ratio is improved by approximately 17.1 % compared to the reference aircraft. Unfavorable effects of the overall configuration are a higher operating empty weight (OEW) of 5.7 % and a higher maximum take-off weight (MTOW) of 1.1 %. The MTOW increases at a lower rate since a lower mission fuel is required by the FSW-NLF aircraft.

At the current state of design, the aircraft is equipped with smart leading edge devices [22, 23] instead of conventional slats. This allows for a stepless and gapless wing surface as well as for high-lift characteristics to fulfill the required take-off and landing performance. However, this kind of high-lift system provides no protection against insect contamination[1]. In this study it is assumed that the wings need to be cleaned on occasion to achieve optimum flight performance. In consequence, the correlation between drag increase, fuel consumption, and aircraft wing cleaning intervals needs to be understood in more detail.

2.1 Implications of Insect Contamination on Aircraft Operations

The accumulation of insect debris on the leading edge of laminar wings has been recognized as one of the most significant operational concerns associated with laminar flow [8]. The threat of contamination is typically limited to operational phases close to the ground. Based on estimations by Humphreys [24] 50-60 % of the insects are collected during the ground run and the balance at low altitude during climb out, final approach and landing. At altitudes above 1,000 ft contamination is normally negligible [24]. During the critical phases the aircraft

[1] Promising protection techniques can be found in [7]. One solution to prevent contamination would be the installation of Krueger-Slats. During critical mission phases the slat would act as a shielding of the leading edge against contamination. But standard Krueger-Slats imply surface interruptions on the lower wing side that cause pre-mature transition.

speed is high enough to cause a rupture of the insect body. These remaining debris create three dimensional roughness elements in the boundary layer, which disrupt the laminar flow and may cause premature transition due to turbulent wedges behind the surface disruption. To generate turbulent wedges, insect residue must exceed a critical height, which is a function of insect size, impact angle and impact speed [7]. Additional factors that define the critical height are the Reynolds number and the relative position of the residue on the wing (state of the boundary layer) [7]. Depending on these factors the share of critical insects on overall contamination is about 9-25 % [18].

The appearance of insects in the atmosphere is generally coupled with factors like season, local terrain, altitude, temperature, humidity and wind speed [17]. Hence, the problem of insect contamination is expected to have distinct regional and seasonal character. Elsenaar and Haasnot conducted a field study at Schiphol Airport to analyze these effects in more detail [8]. Within a time period of one year, weekly visual inspections on eight aircraft were performed in order to quantify the number of insects on the aircraft leading edges. All aircraft were operated in normal airline service on short-to-medium haul missions within a European network. The average contamination rate of all eight aircraft is plotted in Fig. 3 as a function of time. It becomes obvious that contamination is strongly varying with season. During the warm summer months a global maximum is reached, with two local maxima in May and August. In the winter period contamination appears to be no problem. Based on Fig. 3 it can be assumed that contamination within the European region is limited to approximately 35 weeks per year. However, due to the geographic character of the samples, the data can only be used in a limited way to derive a universally valid contamination model and contamination rates.

In practice, the contamination level and the repercussive effects on flight performance of an aircraft with no insect protection actions will also depend on the utilization profile of the aircraft (flight cycles per day) as well as the

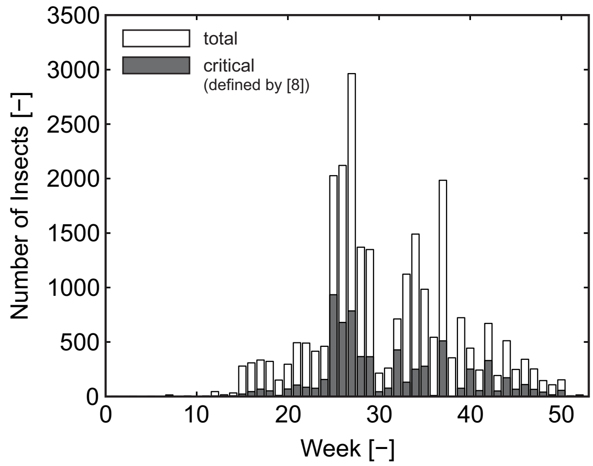

Fig. 3 Number of insect debris on the wing leading edge over a time period of one year [8].

contamination rate per flight cycle. During normal flight operations the aim should be to keep the contamination level as low as possible in order to achieve maximum fuel savings. However, an intensive utilization profile with short turn-around times may not allow for leading edge cleaning between frequent landings. Surface cleaning between each flight seems also to be an unfavorable solution by airlines [25], since this could cause longer turn-around times which may lead to a reduced aircraft utilization. For this reason, a creeping deterioration of flight performance must be expected from flight to flight.

The subsequent section will introduce the models that are used to estimate the loss of flight performance as well as to formulate an optimum time interval for wing cleaning (depending on cleaning method and related duration and cost).

3 Models for Analyzing Operational and Economic Effectiveness

3.1 Modeling of Insect Contamination

To model the interaction between insect contamination and the degradation of flight performance, a fast and simple geometric model is used to simulate the reduction of the optimum laminar area $S_{lam,opt}$ due to turbulent wedges. Depending on the contamination rate and the summed insect debris on the leading edge, the

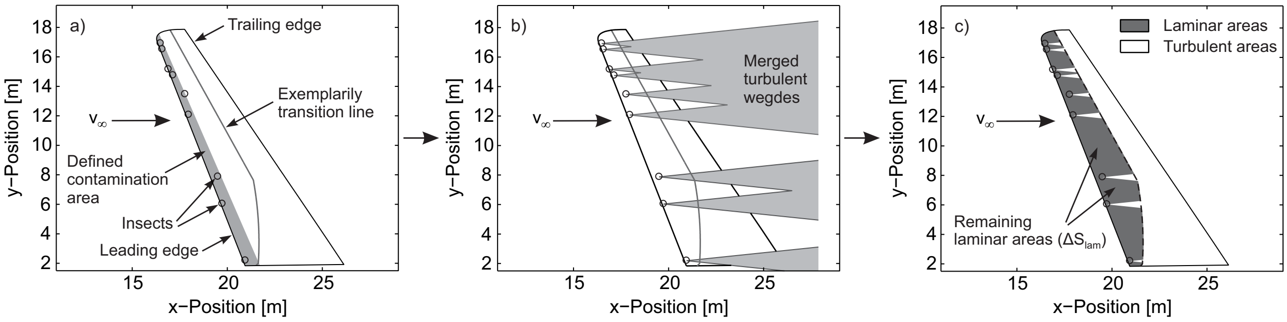

Fig. 4 Process of modeling the impact of insect contamination on available laminar area.

wetted laminar surface is diminished by the area of the turbulent wedges S_{turb} behind the surface disruptions. The quotient of the reduced laminar area including contamination and the laminar area with clean wings is defined as laminar effectiveness E_{lam} (see Eq. 1). During normal flight operations the aim should be to maximize E_{lam} in order to achieve maximum fuel savings. But, as mentioned in the last section, it must be assumed that the ideal laminar area and, as a consequence, the theoretical E_{lam} will not be available in daily operations.

$$E_{lam} = \frac{S_{lam,opt} - S_{turb}}{S_{lam,opt}} = \frac{\Delta S_{lam}}{S_{lam,opt}} \qquad (1)$$

The sequence to calculate E_{lam} is as follows. On the basis of the uncontaminated wing an arbitrary number of critical insects is randomly placed in a user defined area close to the wing leading edge, like exemplarily shown in Fig. 4 a). After the insect positioning, turbulent wedges with a predefined included angle Θ are automatically created in the flow direction. Based on the x-/y-position of the insects and the included angle a polygon is defined which typifies the turbulent wedge downstream of the insect debris. Afterwards all resulting polygons are merged into a single polygon (see Fig. 4 b)). The remaining laminar area ΔS_{lam} can be calculated by overlapping the polygon of the optimum laminar area $S_{\mathrm{lam,opt}}$ with the single turbulent wedge polygon (see Fig. 4 c)). Finally, a functional behavior of E_{lam} can be derived as a function of

- insect number,
- the distribution function of the insects in the wing leading edge area,
- the included angle Θ of the turbulent wedges as well as
- the shape and the position of the transition line.

The resulting aerodynamic deterioration from the contamination simulation will be subsequently used in the mission fuel calculation with the Trajectory Calculation Module (TCM[2] [26]). For this purpose the percentage reduction of E_{lam} is equated with a percentage reduction of the original transition line without contamination to a resulting transition position with contamination (see Fig. 6 in Section 4.1).

3.2 Trajectory Calculation with TCM

Flight mission simulations are performed in order to consider the payload-range characteristics and the flight performance of the reference and the FSW-NLF aircraft within the single mission analysis. The aim is to determine the change in mission fuel and time for different stage lengths and contamination levels due to the operation of the FSW-NLF aircraft compared to the reference configuration. The aerodynamic and engine performance maps resulting from the aircraft design are used to account for the performance of both aircraft. Having aerodynamic characteristic maps for various transition positions available (representing varying total contamination levels), TCM calculates three-dimensional

[2]Developed by DLR Air Transportation Systems

trajectories with distributions of mission fuel and mission time for all routes of interest and different contamination levels based on the total energy model [27]. Using the resulting relative transition position (provided by the insect contamination simulation) for a selected number of insects, TCM interpolates between the available aerodynamic characteristic maps in order to consider the deteriorated flight performance as a result of contamination.

In the course of the mission simulation it is incorporated that the laminar-turbulent transition model (used in the preliminary aircraft design) is only valid within a limited lift coefficient and Mach range due to its calibration with high-fidelity methods[3]. Three boundary conditions must be fulfilled to assure laminar flow. 1) Cruise altitudes must be higher than $31,000$ ft. Below this altitude, a combination of too high Reynolds numbers as well as weather effects cause improper conditions for laminar flow. 2) Cruise Mach number should be between 0.76 and 0.8. Off-design Mach numbers will evoke a pressure distribution not adequate to achieve maximum laminar flow. 3) The lift coefficient c_L should be in a range from 0.45 to 0.55. An assessment of the aerodynamic performance showed that within the defined ranges, no significant changes in laminar flow expansion exist [10]. During trajectory calculation, the TCM analyzes the actual flight conditions and monitors the boundary conditions for compliance. In case of violating one of the boundary conditions, the mission simulator automatically changes from the active laminar aerodynamic performance map to the turbulent one [4].

Depending on the mission length and the respective loading condition of the aircraft, an appropriate initial cruise altitude is automatically selected. Both aircraft start their initial cruise at the optimum altitude for maximum specific range. The cruise itself is implemented as step climb profile with constant altitude between the steps. Results of the mission simulation (fuel and time for both types of aircraft) are transferred to the life-cycle costing tool for further analysis.

3.3 Life-Cycle Costing

The economic viability of a new aircraft concept is essential from an operator's point of view. In this study, the economic analysis is extended from standard direct operating cost (DOC) models to a life-cycle cost benefit analysis in order to model the impact of NLF on the economic viability more accurately. The applied method models all relevant cost elements from an operator's point of view as well as the airline revenues along the aircraft life-cycle. The actual times of occurrence of cost and revenue elements are captured to account for the time value of money. This approach allows for a more flexible evaluation of NLF aircraft, since single cost elements (e. g. maintenance activities) are adjustable by time and cost. All values are escalated over the aircraft life-cycle to account for inflation.

The life-cycle cost calculations are performed with AirTOBS (Aircraft Technology and Operations Benchmark System[5]) [29, 30]. A schematic overview of the program structure can be found in Fig. 5. The basic tool comprises of a flight schedule builder (FSB), a maintenance schedule builder (MSB) and a life-cycle cost benefit module (LC2B). The FSB generates aircraft life-cycle flight schedules based on inputs like aircraft dependent mission flight time, taxi times or turnaround time. Next, the flight schedule is adjusted by maintenance events. This is done by the MSB which simulates maintenance events on discrete, rule-based events (aircraft and engine checks). Each event is triggered by flight cycles (FC), elapsed flight hours or a combination of both. Event characteristics like check interval, downtime, man-hours (MH) or cost are based on Aircraft Commerce data [32]. Based on these data, the MSB

[3]Extension of NLF is essentially dependent on the pressure distribution and the local Reynolds number.

[4]It should be noted that in real flight operations, the change from laminar to full turbulent flow under off-design conditions would be a continuous process and not as sudden as modeled in this study.

[5]Developed by DLR Air Transportation Systems.

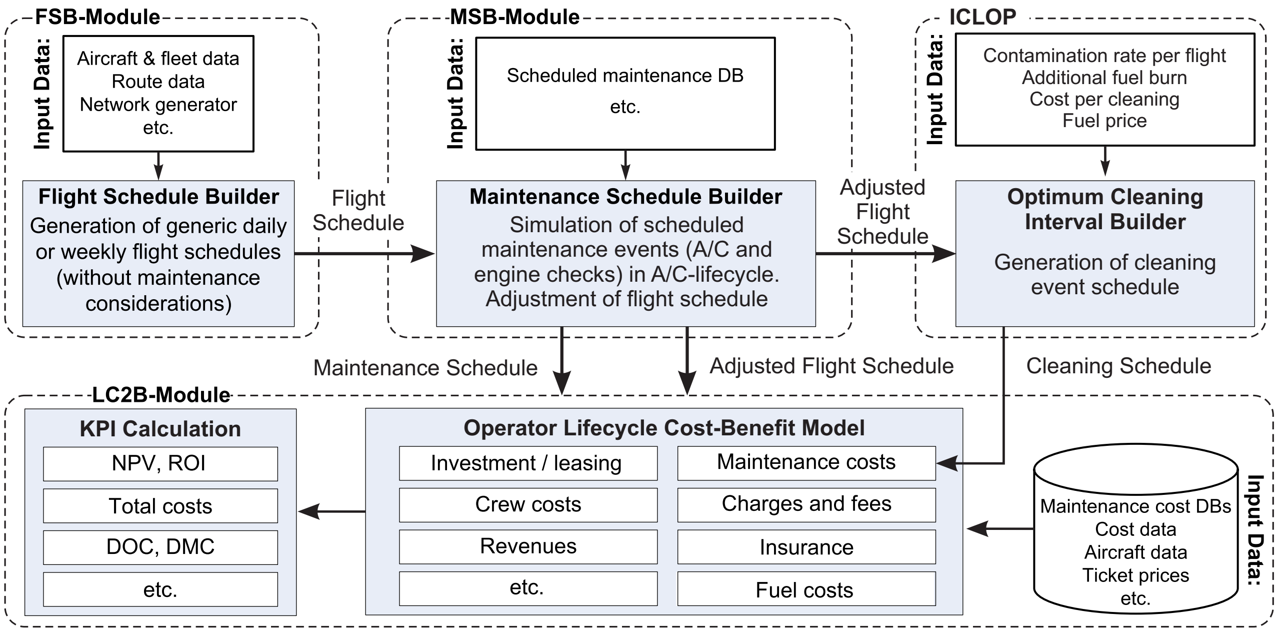

Fig. 5 AirTOBS program structure.

creates a maintenance plan with all occurring maintenance events in the aircraft life-cycle. For this study, AirTOBS was extended by an insect cleaning optimization routine (ICLOP). By applying a Dijkstra-Algorithm [31], the tool calculates an optimized wing cleaning schedule to minimize fuel and cleaning cost based on factors like contamination rate per flight, fuel burn (transferred from TCM) and fuel cost associated with the insect contamination level as well as cleaning cost. The resulting cleaning costs are transferred to the economic assessment, taking place in the LC2B-module. For the assessment and the comparison of different aircraft, Net Present Value (NPV) is chosen as the KPI. The NPV covers all costs and revenues with respect to an investment. All cash flows C_t in the respective operating year t of the aircraft life-cycle are discounted to the reference year at a discount rate r (see Eq. 2). The discount rate represents the minimum acceptable return on capital. A NPV of zero reflects a case where the strived return on capital is reached. The factor C_0 in Eq. 2 represents the initial investment.

$$NPV = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \qquad (2)$$

The focus of the analysis is the added value for the aircraft operator due to the acquisition of NLF aircraft. Based on the calculations for the reference aircraft, the impact of NLF is shown as ΔNPV in which a positive result reflects an economic benefit for the airline due to the operation of NLF aircraft.

4 Assessment of Operational Effectiveness

4.1 Impact of Insect Contamination on Aerodynamic Performance

Fig. 6 depicts analysis results with the insect contamination simulation model for varying contamination levels applied to the FSW-NLF aircraft. In order to account for different span-/chordwise insect distributions, a high number of iterations of random insect positions was performed. The included angle of the turbulent wedges was set to 12° [28]. It becomes obvious that E_{lam} rapidly decreases, correspondingly the resulting transition position, with an increasing number of insects. Even low numbers of critical surface disruptions result in significant penalties. Using a sample of 100 critical insects placed randomly in the wing leading edge region, E_{lam} is decreased by about 45-64 %. This is equivalent to a shifted transition position from 0.55 x_T/c to about 0.2-0.28 x_T/c.

In the context of trajectory calculations the average resulting transition position will be used to determine the influence of contamination level on fuel burn. Furthermore, the chosen total contamination level is split equally to both wings as well as the upper and lower wing, i. e. the resulting transition position is the same for both wings and wing sides.

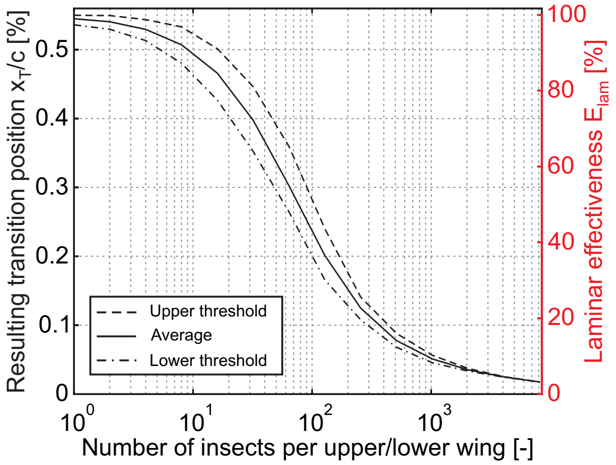

Fig. 6 Trend of laminar effectiveness and resulting transition position depending on the number of insect debris on one wing side (here E_{lam} is related to only one wing side (upper or lower wing)).

4.2 Mission Simulation Results

Single mission simulations are carried out for the reference aircraft and the FSW-NLF configuration to determine required mission fuel for routes between 250 and 4,750 km. An exemplary trajectory calculated for a 3,000 km mission with conditions of altitude, Mach number and lift coefficient is shown in Fig. 7. The flight phases where laminar flow conditions are fulfilled are shaded in grey.

Like shown in Fig. 8, the computed trajectories are analyzed for relative change in mission fuel due to the operation of the NLF aircraft. Besides an operation with optimum laminar effectiveness (uncontaminated wings), different contamination scenarios as well as the operation with fully turbulent wings ($E_{lam} = 0$) are plotted. It is apparent that the change in mission fuel strongly depends on the flown stage length and contamination level. On

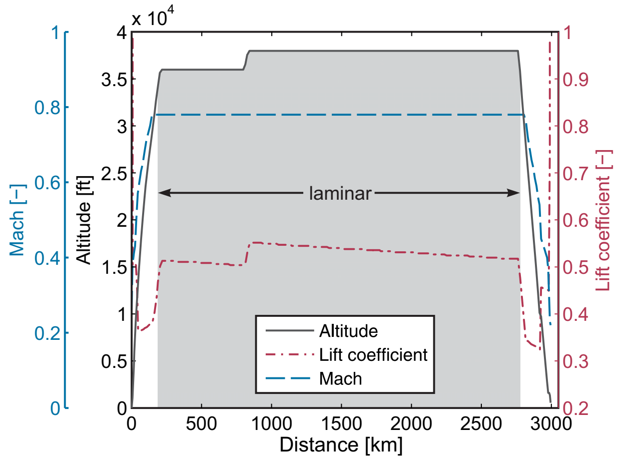

Fig. 7 Trajectory for a 3,000 km mission with conditions of altitude, Mach number, lift coefficient and laminar state.

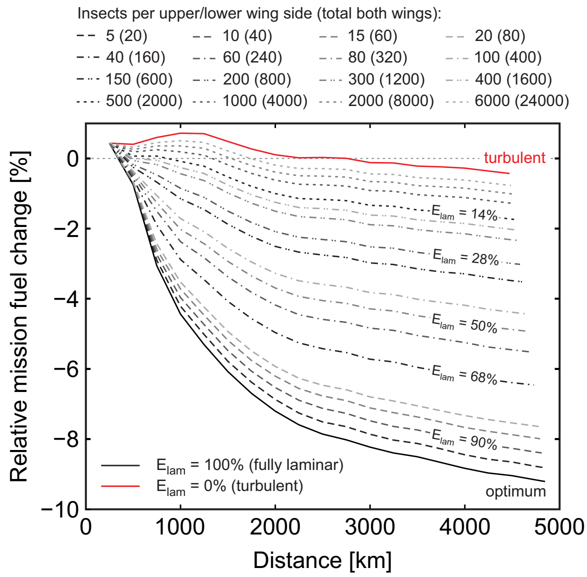

Fig. 8 Impact of insect contamination on fuel efficiency (bulging of the fuel saving curves for missions around 1,000 km originates from different optimum initial cruise altitudes).

missions shorter than 500 km, no fuel benefit exists. This is due to the effect, that the required boundary conditions for laminar flow are not fulfilled. Consequently, the turbulent aerodynamic performance map is used in TCM. The maximum fuel saving potential is reached on long routes. With up to 9.2 % mission fuel reduction, the results are in the order of magnitude of other studies [2, 3, 5]. This value shrinks to 3 % for missions around 750 km. An operation with fully turbulent wing shows no benefit for routes shorter than 2,000 km. For longer routes, the fuel burn is in the order of the reference aircraft with a maximum advantage of 0.4 %. This can be ascribed to lower induced drag caused by the higher aspect ratio of the FSW-NLF aircraft. However, compared to the operation with $E_{lam} = 1$ a range loss of about 375 km arise. Looking at the resulting in-service degradations as a result of insect contamination, the potential fuel saving is substantially reduced. An exemplary total contamination level of 400 insects causes a cutback of the relative mission fuel change to 4.4 % on long missions and 1.1 % for stage length of 750 km. For a total contamination rate of 2000 insects or more, it seems that the wing runs into a saturation with insects (see also Fig. 6). Despite a significant increase of the number of insects, the additional loss of fuel savings is considerably low. Remarkable losses of fuel benefit mainly emerge from total contamination levels below 2000 insects.

5 Assessment of Economic Effectiveness

5.1 Assessment Assumptions

In order to account for uncertainties in the life-cycle cost analysis, different scenarios are applied to cover a wide band of operational boundary conditions (see Tab. 2). The NPV assessment is performed for the design range as well as a route-mix for an aircraft life-cycle of 20 years. Evaluating only the design range would not be sufficient for an aircraft operator, since the typical utilization of the aircraft differs significantly from the aircraft design point [33]. The route-mix composition, with its respective mission length and relative flight frequencies, is derived on the typical utilization profile of today's short-to-medium range aircraft (see [19]). Range corresponding fuel data are gathered from the single mission simulation.

In this study, especially the change of maintenance effort and costs linked to the NLF aircraft operation including insect contamination are of special interest. Due to the lack of experience of typical yearly

Table 2 Economic assessment assumptions and scenarios.

General assessment assumptions	
Aircraft life-cycle	20 years
Interest rate	7 %
Load factor	80 %
Mission length	
Design-Range	
4,800 km (2 FC per day)	
Route-Mix	
600 km (2 FC per day)	
1,400 km (1 FC per day)	
2,800 km (1 FC per day)	
Fuel price scenarios (FP) (final price after 20 years)	
0.32 USD/kg ; 0.69 USD/kg ; 1.05 USD/kg	
FSW-NLF aircraft related assumptions	
Insect contamination scenarios (CS)	
3 Yearly contamination rates (Fig. 9)	
Leading edge cleaning cost	
(Sum of required labor power and material per event)	
0 USD ; 150 USD ; 300 USD ; 450 USD ; 600 USD ; ...	
750 USD ; 900 USD ; 2,500 USD ; 5,000 USD	
Aircraft price	
−7.5 % ; −3.75 % ; ±0 % ; +3.75 % ; +7.5 %	

insect contamination rates, three scenarios regarding the contamination rate per flight cycle are implemented in ICLOP and the economic analysis. As can be seen from Fig. 9, contamination[6] starts around week 10 and ends in week 48. Highest contamination rates are reached in the warm summer months. Although it would be desirable from a performance point of view to clean the wing leading edge as often as necessary (e. g. between two flights), from an airline perspective, the shortest allowable time interval to remove insect residues would be a cleaning during the curfew hours (10pm-6am) [25]. Therefore, the shortest possible maintenance interval in ICLOP was set to be a nightly cleaning. Experiences with respect to time effort and cost for a ground based cleaning procedure are available for standard aircraft exterior cleaning [34, 35, 36]. Based

[6]Numbers represent total contamination per flight cycle, i.e. for both wings as well as upper and lower wing side.

on these numbers and the knowledge of the contaminated area, cost and time scenarios for a single leading edge cleaning process were derived (see Tab. 2). In order to consider

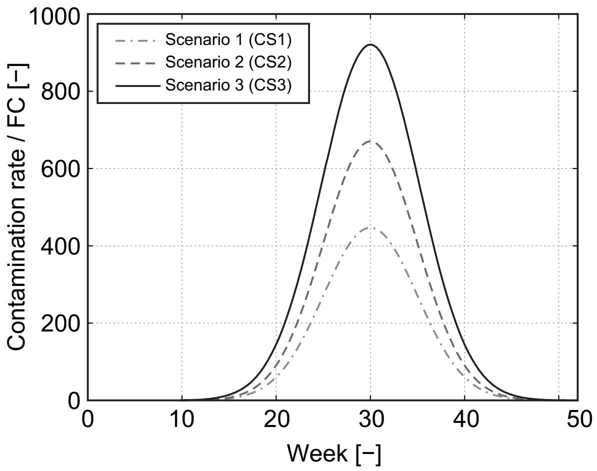

Fig. 9 Insect contamination scenarios.

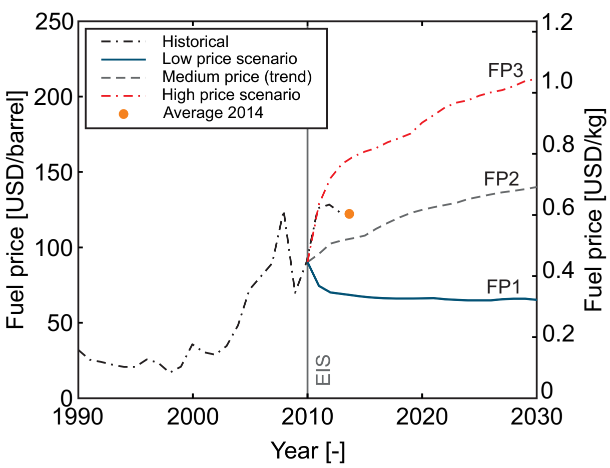

Fig. 10 Jet fuel price scenarios (adopted from the U.S. Energy Information Administration (EIA)).

different initial investments of the airline due to the NLF aircraft acquisition, five prices for the NLF aircraft were derived based on manufacturer price lists for today's short-to-medium range aircraft. Factors that will influence pricing are, among others, the manufacturer's non-recurring and recurring cost to develop and manufacture NLF aircraft.

One key factor for the application of laminar flow technology is the historical and future development of airline fuel cost. With the world's growing energy consumption and limited resources, the fuel price could become an even more important factor for airline economics. To cover this important economic aspect, three different fuel price trends are used in the assessment to cover possible future trends (see Fig. 10).

5.2 Economic Effectiveness Results

Before the outcomes of the economic life-cycle analysis will be explained in more detail, some exemplary results of the insect cleaning routine with focus on route-mix operation are presented. Fig. 11 depicts some results of the cleaning interval optimization for three cleaning cost scenarios.

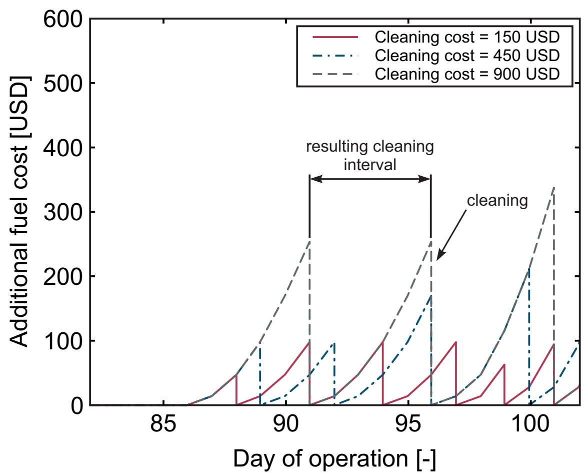

Fig. 11 Example for optimum cleaning intervals (fuel price scenario 2, insect contamination scenario 2, route-mix operation).

Each step in the figure characterizes a cleaning process carried out on a certain day of aircraft operation. The ordinate shows the cumulative additional fuel cost, compared to the uncontaminated FSW-NLF wing with optimum fuel saving performance, as a result of insect contamination. After a cleaning event the additional fuel cost are reset to zero and the daily fuel accumulation is started anew. Depending on the assumed cleaning cost, different cleaning intervals are suggested by the Dijkstra-Algorithm to minimize fuel and cleaning related maintenance life-cycle cost. In general the cleaning interval depends on fuel

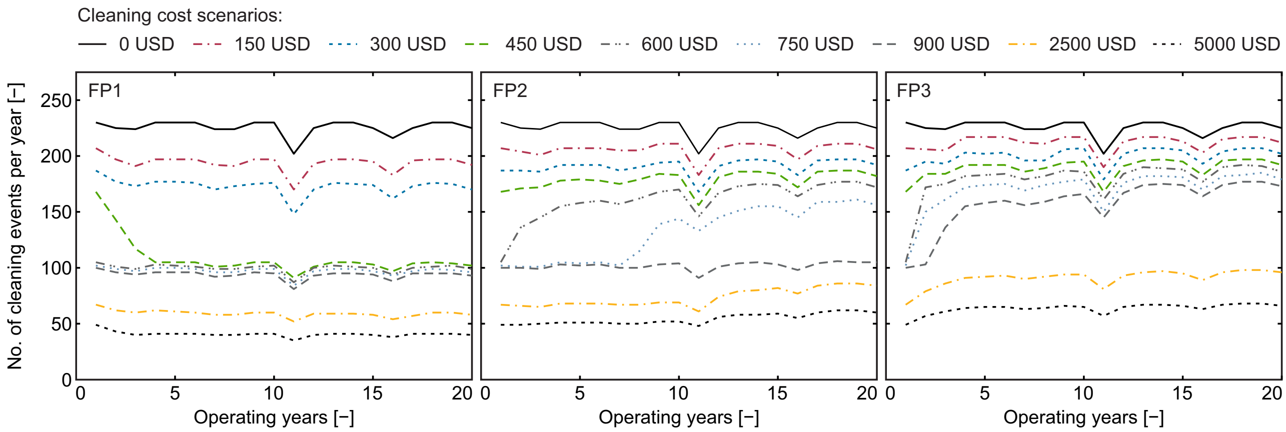

Fig. 12 Change of cleaning intervals per year as a function of fuel price and cleaning cost (contamination scenario 1, route-mix operation; the drop of cleaning events after 11 operating years originates from the D-check).

price, cleaning cost (material and required labor), contamination rate and daily flight cycles.

The number of yearly cleaning events for the three fuel price scenarios and varying cleaning costs are shown in Fig. 12. Depending on the fuel price and the incurred cleaning cost, different cleaning tactics are proposed by the optimizer. The upper threshold of yearly cleaning events is formed by the scenario with no additional cost for a cleaning event. To minimize cost, in this case only the additional fuel cost, a daily cleaning schedule is chosen in the time period with insect contamination for all three fuel prices. Looking at the first fuel price scenario, three cleaning tactic clusters can be identified. Within the first cluster (cleaning prices up to 300 USD per event) a 2 day-/1 day interval leads to minimum fuel and cleaning cost. In correlation with a decreasing fuel price in the first four operating years, the cleaning tactic changes for the 450 USD cost scenario from a 2 day-/1 day schedule to a 3-2-1 schedule, at which a daily cleaning is only carried out in the period with maximum contamination rates. For event cleaning cost between 600 USD and 900 USD the optimum cleaning interval shifts to a 3 day-/2 day schedule. Event cleaning cost of more than 2,500 USD result in intervals longer than 3 operating days. Compared to the first fuel price scenario, the number of cleaning events generally drift to more occasions for the other fuel cost scenarios. Furthermore, a change of tactics can be noticed for some cleaning cost scenarios in conjunction with the rising fuel cost. Major differences between the different cleaning cost scenarios are mainly driven by varying cleaning schedules in the edge regions of the yearly contamination rate distribution. In the inner area of the insect distribution function all cost scenarios up to 900 USD are characterized by a daily leading edge cleaning.

The influence of other assessment assumptions can be concluded as follows. The influence of the applied contamination scenarios on the cleaning schedule is characterized by a slight increase of yearly cleaning events. For the operation on design range the number of yearly cleaning events are comparable with those for the route-mix operation. However, changes in cleaning tactics are less distinctive.

The dependency between additional life-cycle fuel cost as a result of contamination and life-cycle cleaning cost (associated as additional maintenance cost) is shown in Fig.13. Using a no maintenance cost scenario as starting point, the fuel benefit loss compared to the operation of the uncontaminated FSW-NLF aircraft becomes apparent. The penalty of insect contamination is in the range of 1.7 to 2.3 %. Shorter cleaning intervals than the assumed one, e. g. before each flight, would allow for a penalty reduction and an approximation to the optimum benefit. The above-mentioned change of cleaning tactic, can also be found in this figure (step from 300 to 450 USD cleaning cost). For the aircraft operation this step could be of special interest. By decreasing the cleaning cost from 450 to 300 USD a fuel saving of 0.9 % (0.72 Mio.USD) can be achieved over the aircraft life-cycle. Although this comes along with a slight increase of maintenance cost (0.1 Mio.USD) as well as a higher number of cleaning events (from 2,173 to 3,460), it would be worth to fulfill this change of tactic from an overall cost perspective. In sum, the additional maintenance effort due to wing leading edge cleaning counteracts the overall economic viability of the FSW-NLF. However, it constitutes a necessary activity to optimize the FSW-NLF aircraft operation and the resulting fuel burn benefit.

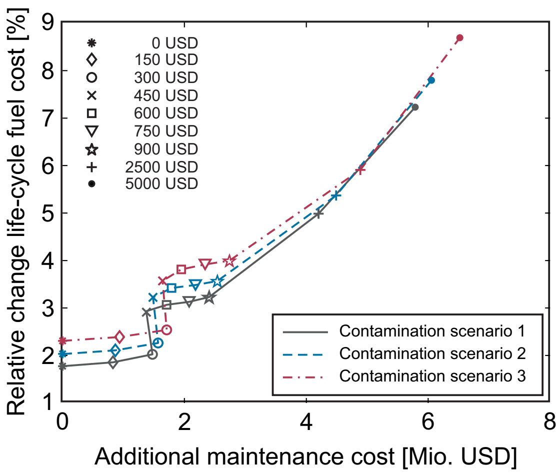

Fig. 13 Exemplary interrelation of life-cycle fuel cost change and additional maintenance cost due to wing leading edge cleaning (fuel price scenario 1, route-mix operation).

The relative change in NPV due to the operation of FSW-NLF aircraft instead of conventional configurations is shown in Fig. 14-17 for a set of assessment scenarios. All figures point out the beneficial effect of laminar flow in terms of an increasing ΔNPV with increasing fuel price. Fig. 14 highlights that the economic benefit is maximized for operation at design range with optimum laminar flow ($E_{lam} = 1$) and no additional operating cost. Further aspects that are pointed out in the following discussion lead to an overall reduced improvement. Incorporate the effects of insect contamination in the assessment, ΔNPV decreases by 16-24 % (depending on the selected contamination scenario) as a result of a reduced operational effectiveness. Economic effectiveness is not given with high escalation rates of cleaning cost and low fuel prices. As a function of selected cost and contamination scenario different incremental fuel prices emerge, which must be exceeded to create an economic operation of the FSW-NLF aircraft. For example, event cleaning cost of 5,000 USD connected with the second contamination scenario would require a fuel price development which is above the second fuel price scenario.

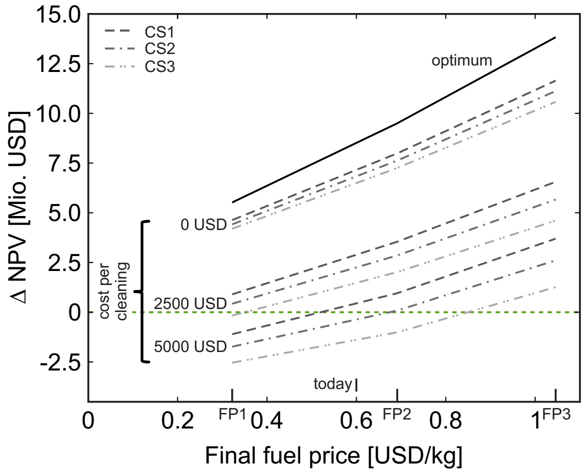

Fig. 14 Change of ΔNPV due to different insect contamination rates and selected event cleaning cost (design range operation).

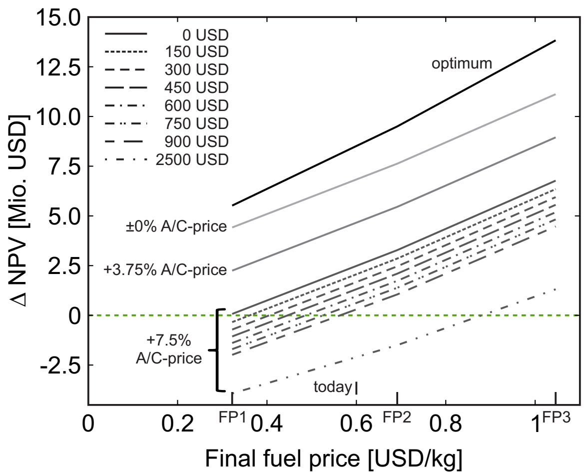

Fig. 15 Change of ΔNPV with increasing cleaning cost per event and aircraft price (design range operation, contamination scenario 2).

As shown in Fig. 15, higher investment costs also provoke a reduction of economic advantage. Economic effectiveness still exists for an escalated aircraft price of up to 7.5 % (no additional maintenance cost) for all fuel price scenarios. A further cost escalation due to cleaning cost result in negative ΔNPV for specific fuel prices.

From an airline perspective the assessment of the FSW-NLF aircraft including a realistic route-mix operation is of higher interest. Due to the operation on less laminar favorable missions (see relative fuel benefit in Fig. 8) the economic benefit is less distinctive. At the same time, the allowable cleaning and investment costs shift to lower values (compare Fig. 14/16 and Fig. 15/17). The reduced aerodynamic performance as a result of insect contamination causes a reduction of the optimum ΔNPV of 36-41 % for low fuel prices and 30-39 % for high fuel cost. If expenditures of cleaning cost per event stay considerably below 900 USD, an economic advantage can be achieved by the FSW-NLF aircraft. For cleaning cost of 900 USD or more, the ΔNPV slips partially to negative values. Very high escalation rates of cleaning cost (like shown in Fig. 14) lead to a non-economic operation. According to Fig. 17, the margin for aircraft price adjustments is also considerably smaller compared to design range operation. Low fuel prices allow only for an escalation of event cleaning cost in the order of 600 USD without any additional investment cost. However, high fuel prices set a cost limit at 3.75 % aircraft price rise and 450 USD maintenance cost.

Based on Fig. 14-17 it is hard to deduce the trade-off of allowable expenditure which will result in a positive ΔNPV. For this reason isolines charts (cost combinations where ΔNPV=0) were created, which account for the three fuel price scenarios, different contamination rates as well as design range and route-mix operation (see Fig. 18 and 19). The indicated lines represent the limiting cost combinations of aircraft price and cleaning cost to create a positive ΔNPV in favor of the FSW-NLF aircraft. To ensure an economic airline operation it is

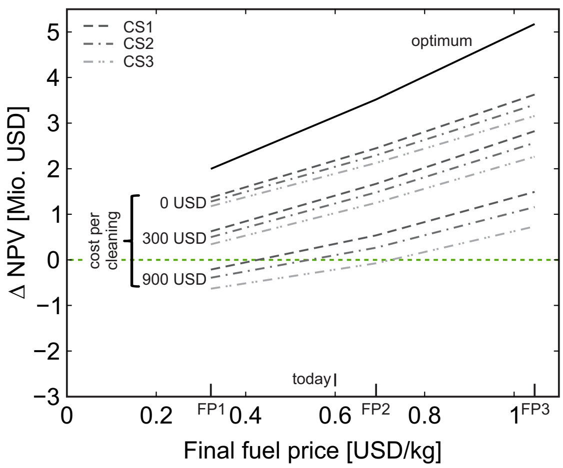

Fig. 16 Change of ΔNPV due to different insect contamination rates and selected event cleaning cost (route-mix operation).

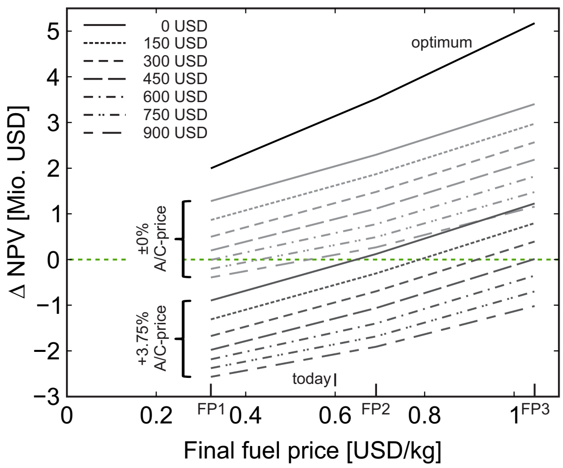

Fig. 17 Change of ΔNPV with increasing cleaning cost per event and aircraft price (route-mix operation, contamination scenario 2).

necessary that the emerging cost combination stays beneath the limiting curves of ΔNPV=0. Both figures show that a rising fuel price as well as lower insect contamination rates allow for additional expenditures to achieve economic viability. Comparing Fig. 18 and Fig. 19, the isolines for ΔNPV=0 are shifted significantly to lower cost for an operation on a realistic route mix. Key factor is the reduced fuel saving potential on off-design routes. As a consequence, the beneficial impact of fuel savings on the economic performance is compensated earlier by the negative repercussions of increased aircraft price or maintenance cost. Taking today's fuel price into account, an exclusive operation of the

FSW-NLF aircraft on a route-mix would still be profitable for an aircraft price escalation in the order of 4.5 % (no additional maintenance cost/depending on the contamination scenario). This value shrinks with increasing cleaning cost. If cleaning cost stay below approximately 1,200 to 1,400 USD (without additional investment cost/depending on the contamination scenario) the economic effectiveness for the airline would also be given.

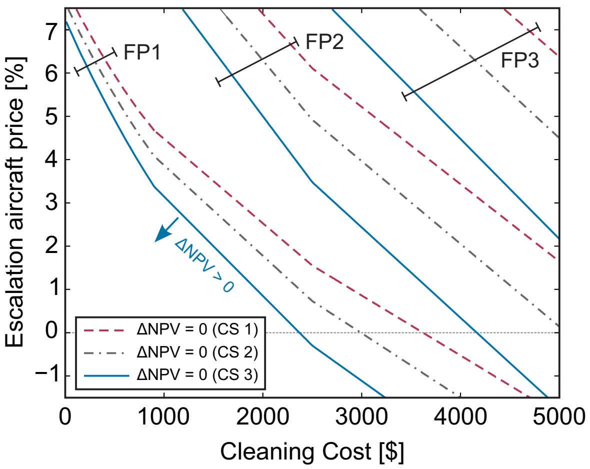

Fig. 18 Allowed parameter combinations of aircraft price and cleaning cost resulting in a positive ΔNPV as a function of fuel price and contamination rate scenario (design range operation).

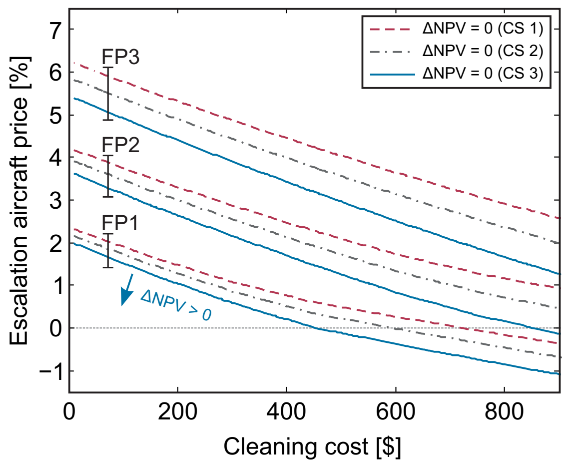

Fig. 19 Allowed parameter combinations of aircraft price and cleaning cost resulting in a positive ΔNPV as a function of fuel price and contamination rate scenario (route-mix operation).

6 Conclusion and Outlook

This paper describes an enhanced system analysis process to evaluate the effects of insect contamination on fuel efficiency and airline economics of FSW-NLF aircraft. The applied assessment chain comprises tools for insect contamination simulation, single mission fuel analysis, and aircraft life-cycle costing. The presented mission simulation results highlight the significant fuel efficiency benefit of up to 9.2 % by operating the FSW-NLF aircraft instead of the reference configuration. However, it was found that the achievable fuel benefit strongly depends on mission length as well as on aerodynamic deterioration as a result of insect contamination. Besides the analysis of operational effectiveness, the economic viability of NLF aircraft under realistic operational boundary conditions, incorporating the implications of insect contamination, was of special interest. By carrying out a cost analysis of additional fuel burn cost (due to reduced laminar effectiveness) and aircraft cleaning cost, optimum time intervals to clean the wing leading edge of a FSW-NLF aircraft were formulated. It can be concluded, that the appropriate time interval to clean the wing leading edge strongly depends on cleaning cost per event, fuel price, contamination rate and aircraft utilization. Although the additional maintenance effort counteracts the overall economic viability of the FSW-NLF aircraft, it constitutes a necessary activity to optimize the aircraft operation and the resulting fuel burn benefit. The interaction and combination of operational boundary conditions such as laminar effectiveness, fuel price and non-fuel related cost (like aircraft price and maintenance cost) play an important role for the economic effectiveness of laminar flow aircraft.

In future studies, the introduced analysis and assessment process will be expanded by further operational aspects and risks to laminar flow (like cloud encounter/ice crystals). While this study focuses only on operational and economic effectiveness, it is planned to widen the analysis scope also to ecological effects in order to give a more comprehensive answer for the introduction of FSW-NLF aircraft in the air transportation system. Besides a reduction of gaseous emissions and climate impact, noise emission characteristics due to the aircraft layout (leading edge high-lift device designed as gapless droop nose and shielding of engine noise by the wings) could also be of interest.

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