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SELECTED CURRENT CHALLENGES IN THE DEVELOPMENT OF HYBRID LAMINAR FLOW CONTROL ON TRANSPORT AIRCRAFT

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Abstract

The application of hybrid laminar flow control (HLFC) on commercial aircraft is one of the most promising fuel reduction technologies. Although this topic has been the subject of research and development for decades, the technology has not yet managed to establish itself successfully. An important factor is the uncertainty of the operators regarding the resulting overall efficiency, i.e., the ecological and economic efficiency achieved under realistic operational boundary conditions. This includes additional maintenance as well as the loss of laminarity under non-ideal operating conditions. From the manufacturers' point of view, the HLFC technology is also not yet satisfactorily mastered. Current research and development activities focus on time- and cost-efficient production while complying with high certification requirements. Using latest sub-technologies, these questions are tackled in several projects within the European Clean Sky 2 program. This paper addresses a few selected challenges from an overall aircraft impacts' point of view and presents the taken approaches to solve these. Through close collaboration between all disciplines and the inclusion of the assessment in the early design phase it is aimed to develop a successful complete system representing a significant step towards market-ready hybrid laminar posture.

Nomenclature

A/C	Aircraft	**HTP**	Horizontal Tailplane
ACARE	Advisory Council for Aeronautics Research in Europe	**IATA**	International Air Transportation Association
ECHO	Evaluation of a Certified HLFC Elevator Operation	**OAA**	Overall Aircraft Assessment
GBD	Ground Based Demonstrator	**TRL**	Technology Readiness Level
HLFC	Hybrid Laminar Flow Control	**WIPS**	Wing Ice Protection System

1. INTRODUCTION

Since the beginning of commercial air travel, airplanes have brought the world closer together. In the latest annual review of the International Air Transport Association (IATA) it is stated that airlines connected a record number of 22,000 unique city pairs around the globe. Compared to the mid-1990s, this represents a doubling in the connectivity [1]. This demand is expected to grow steadily in the future. According to latest forecasts by industry experts the total number of passengers will double over the next 15-20 years, leading to an enormous demand on additional aircraft [2–4].

The downside of this development is that aviation is responsible for about 12% of global CO_2 emissions within the transport sector. Around 80% of these emissions are caused by flights over 1500 kilometers for which there are no viable alternatives, such as intercontinental or long-haul flights [5,6]. In addition to carbon dioxide, aircraft emit noise and particles and gases such as nitrogen oxides, which also contribute to climate change.

The international aviation community is aware of these environmental impacts. In order to take responsibility the Advisory Council for Aeronautics Research and Innovation in Europe (ACARE)[1] has formulated several ambitious goals, which have been updated with the European vision "Flightpath 2050". These are (amongst others) [7]:

- a reduction in CO_2 emissions by 75%,
- a reduction of NO_x emissions by 90% and
- a reduction of the perceived aircraft noise by 65%,

compared to emissions from typical new aircraft from the year 2000.

[1] ACARE was established by the European Commission in 2001.

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Clean Sky 2 aims to be the main contributor to these goals. It is a public-private-partnership between the European Commission and the European aeronautics industry and the successor of the initial Clean Sky programme.

One major field of research and development of environmental friendly aircraft is the aerodynamic efficiency. The objective is to reduce drag while maintaining the generated lift. This reduces the thrust required by the engines[2], thus saving fuel, CO_2 and NO_x emissions. One of the most promising aerodynamic technologies for commercial aircraft is laminar flow control. It aims to increase the chordwise extent of the laminar boundary layer and can be applied to the wing, tailplane, vertical stabilizer and engine nacelles. The laminar-turbulent transition is shifted from stagnation point proximity to up to 50-60% downstream [8]. Out of the available flow control methods, Hybrid Laminar Flow Control is the most promising for future mid- to long-range aircraft. HLFC is characterized by combining boundary layer suction over the first 15-20% of the chord with an airfoil design which supports the transition through specific pressure distribution characteristics [9].

2. CURRENT PROJECTS IN CLEAN SKY 2 DEALING WITH HLFC

The application of HLFC is addressed in two (physical) demonstrator centered projects and one flight test demonstration. This paper focusses on the former two projects called ECHO and HLFC-Win. Both are led by Airbus Germany and have the goal to develop a Ground Based Demonstrator (GBD) fulfilling a certain Technology Readiness Level (TRL). TRLs are a type of measurement used to assess the maturity of a technology aiming to create and sustain a comparable and systematic scale across various applications [10]. Figure 1 shows the nine levels with their brief title.

2.1. ECHO

The project ECHO (Evaluation of a Certified HLFC Elevator Operation) is devoted to the application of HLFC on the Horizontal Tailplane (HTP) of the current Airbus A350. While the expected fuel reductions are rather modest, ECHO acts as a “lighthouse project”. That is, state-of-the-art aerodynamics, system and structural design are combined with latest manufacturing technologies to understand and strengthen the required interdisciplinary efforts. Due to the relatively small scale of the HTP, innovative and risky sub-technologies can easily be tested not only in theory, but also under laboratory conditions. With the final GBD aiming at TRL6, the main focus of this project is the development of structure and manufacturing concepts considering a weight and cost optimized design as well as high production rates. The valuable insights are then transferred to the “sister project” HLFC-Win, where the expected impact is much higher.

The consortium within this project consists of the research partner DLR and the industrial counterpart Aernnova.

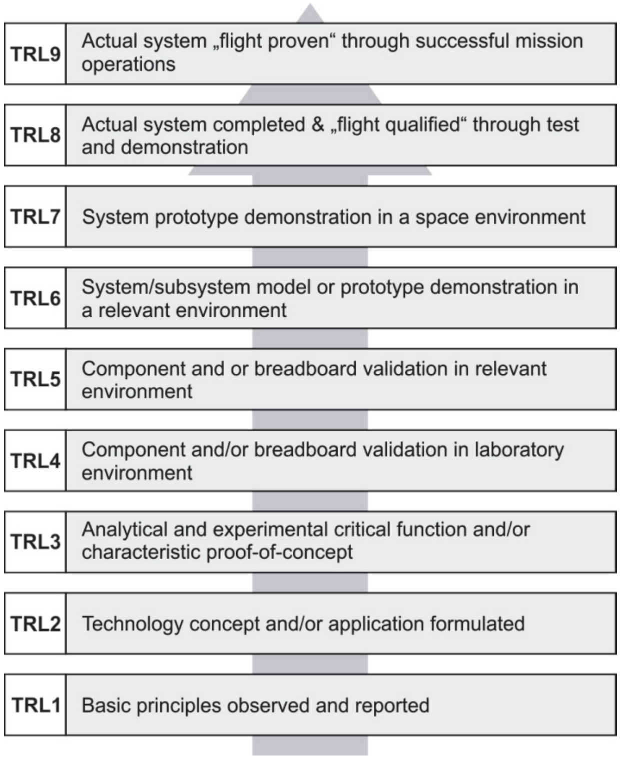

Figure 1: Technology Readiness Levels [10]

2.2. HLFC-WIN

The project HLFC-Win is closely linked to ECHO and aims to develop a wing with HLFC for a long-range aircraft while focussing on maximizing the overall efficiency (economic and operational). In contrast to ECHO, the reference aircraft is not an actual existent and flying aircraft, but a research based aircraft design called XRF1 developed by Airbus to support the collaboration with the external research community.

The consortium within this project consists of the following partners with their respective responsibilities:

Aernnova	Consortium Lead and responsible for ground based demonstrator
DLR	Responsible for the HLFC wing design including aerodynamics & structures as well as net benefit assessment
ONERA	Responsible for wind tunnel activities and overall drag benefit assessment
SONACA	Responsible for the wing ice protection system (WIPS) and Kruger kinematics

[2] Assuming the aircraft velocity stays unchanged

3. SELECTED CHALLENGES

This chapter presents two challenges, which have recently been dealt with and thus may give some valuable insights into the projects latest challenges from an overall aircraft assessment point of view.

3.1. OPERATIONAL DEGRADATIONS (ECHO)

The first challenge deals with operational degradations and has just recently been addressed in ECHO to reach TRL4. To do so, the limitations of performance had to be identified and where possible, quantified.

As mentioned in several previous projects and publications, the contamination of the leading edge due to insect debris is considered as one of the most critical limiting factors [9]. Depending on the remaining height of the insect residues, the contamination may cause turbulent wedges downstream. This can decrease the overall laminar area significantly, as Figure 2 shows.

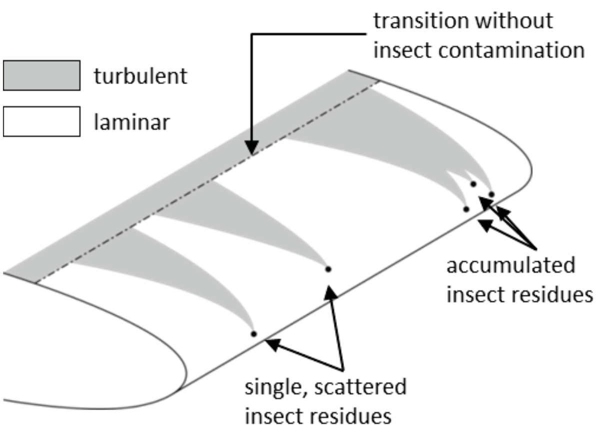

Figure 2: Insect contamination on the leading edge [11]

It is obvious that the loss of laminarity increases with the number of insects. However, this relationship is by no means linear. Depending on the span- and chordwise position of the residues, the turbulent wedges may or may not overlap, which leads to an individual pattern and thus loss of overall laminarity. In order to address this problem adequately, multiple tasks have to be performed:

1. Estimate the relationship between the loss of laminarity and the number of insects on the laminar area
   a) *Develop a model for determining the locational probabilities of insect contamination (chordwise, including the shape of the airfoil)*
   b) Perform a simulation with a random spanwise distribution and record the loss of laminarity
   c) Obtain transfer functions for a worst, best and expected case scenarios
2. Estimate the number of insects which can be expected to stick on the laminar leading edge area for each flight cycle throughout the year
   a) *Develop an appropriate insect population model*
   b) Make use of a global airport weather database to feed the model
   c) Simulate the climb and descent of the HTP leading edge with a) and b)
   d) Validate models using available literature

The highlighted tasks 1a) and 2a) shall be presented in more detail.

3.1.1. CONTAMINATION MODEL ON HTP (1A)

The goal of this task is to be able to predict (to some extent) at which chord positions insects are more likely to stick. This depends on a number of factors, out of which the airfoil geometry is focused on here.

Considering an evenly distributed insect swarm as shown in Figure 3 and a microperforated piece of the airfoil which moves towards it (with the constant velocity v) under a perpendicular angle (called α), the number of insects sticking to the sheet (of the width Δd) will be at its maximum. This is illustrated by the red highlighted circles within the swarm. If the angle is now varied as shown on the right hand side, the expected contamination will decrease as the projected relevant surface shrinks.

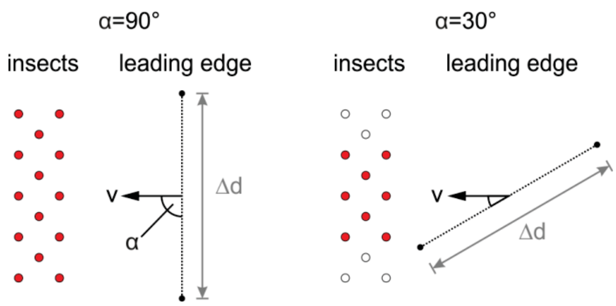

Figure 3: Insect contamination depending on angle

This relationship is easily described by the sin-function:

$$IC = \Delta d \cdot \sin(\alpha)$$

where IC represents the relative insect contamination. It is now assumed that the probability P of an insect to stick on this particular piece of sheet, defined by its chord position c and tangential angle $\alpha(c)$, is:

$$P(c) = \frac{IC(c)}{IC_{\max}} = \frac{\Delta d \cdot \sin(\alpha(c))}{\Delta d} = \sin(\alpha(c))$$

This local insect contamination relationship can now be applied to the full airfoil by dividing latter into piecewise constant segments. The result is shown in Figure 4 for the top side (red) and bottom side (blue). As expected, the foremost part of the leading edge would suffer from the highest contamination, whereas the airfoil will probably stay free of insects for chord lengths above 20% on the bottom and 30% on the top side.[3]

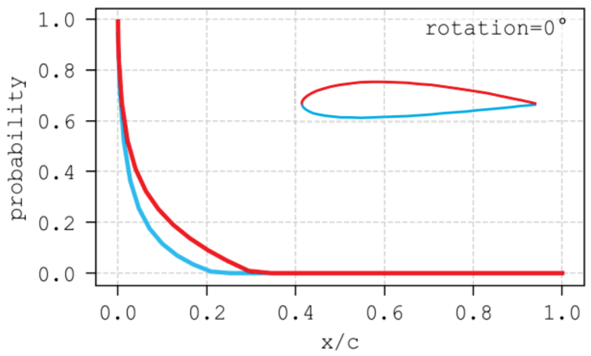

Figure 4: Modeled chordwise probability of insect contamination

It should be noted that this probability only considers the geometric constraints only and neglects any repercussions of the surrounding airflow on the contamination. Since the HTP will experience varying angles of attack, e.g. through trimming, the chordwise probabilities were also obtained for different rotational angles. The results are shown in Figure 5.

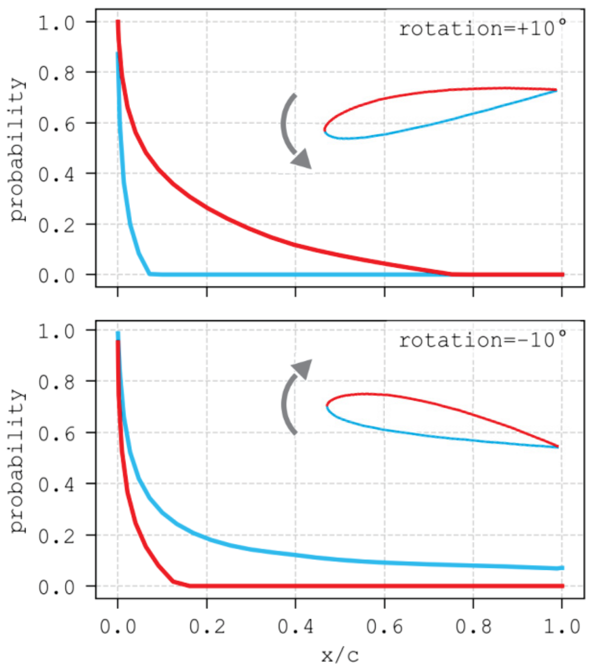

Figure 5: Chordwise contamination probability at different angles

The next step is to perform a discrete insect accumulation simulation using these chordwise probability distributions.

[3] Note that the shown curves and values were calculated for a generic NACA 2415 airfoil instead of the actual A350 HTP to avoid intellectual property issues.

The methodology and some results (albeit for another case and geometry) can be found in Ref. [12].

3.1.2. INSECT POPULATION MODEL (2A)

The goal of this task is to be able to predict (to some extent) how big the average insect population is for a given situation. The chosen parameters for the model are altitude, temperature and wind speed. For a more complete picture, the humidity and local fauna could be taken into account. However, the (admittedly short) search for aviation relevant data to feed the regression analyses was only successful for the former mentioned three parameters[4].

The procedure to obtain the overall population density $\rho_{\mathrm{ins}} = f(H,T,W)$ model is relatively straightforward. First, the dependency of ρ_{ins} on each parameter (altitude: H, temperature: T and wind speed w) is modeled and normalized. Afterwards, these are combined by a simple multiplication[5], i.e.:

$$\rho_{\mathrm{ins}}(H,T,W) = \rho_{\mathrm{ins}}(H) \cdot \rho_{\mathrm{ins}}(T) \cdot \rho_{\mathrm{ins}}(W)$$

The altitude dependency was found in absolute values (i.e. insects per million cubic feet) from [13]. Assuming that the maximum density can be found at ground level, the used regression function is:

$$\rho_{\mathrm{ins}}(H) = a_H \cdot \exp(b_H \cdot H) + c_H \cdot \exp(d_H \cdot H)$$

The temperature and wind dependencies were both available in relative population density [14–16] and were modelled using the Gaussian bell equation:

$$\rho_{\mathrm{ins}}(T) = \exp\left(-\frac{(T-\mu_T)^2}{2\sigma_T^2}\right)$$

$$\rho_{\mathrm{ins}}(W) = \exp\left(-\frac{(W-\mu_W)^2}{2\sigma_W^2}\right)$$

Figure 6 shows the data as well as the regression functions used. The final function for the overall model is:

$$\begin{aligned}&\rho_{\mathrm{ins}}(H,T,W) = \\ &[0.091 \cdot \exp(-0.003 \cdot H) + 0.919 \cdot \exp(-0.041 \cdot H)] \\ &\cdot \left[\exp\left(-\frac{(T-24.43)^2}{2\cdot(-8.03)^2}\right)\right]\left[\exp\left(-\frac{(W-3.1)^2}{2\cdot(4.44)^2}\right)\right]\end{aligned}$$

The next step for the overall methodology of considering the insect contamination is the simulation of the aircrafts' route network throughout the year, combined with the local weather situation and insect accumulation model described previously.

[4] Thankfully, all of these datasets were nicely collated in Ref. [13].
[5] Although it expected that the three used parameters show a high correlation to one another, a detailed statistical analysis was not performed for this particular population model.

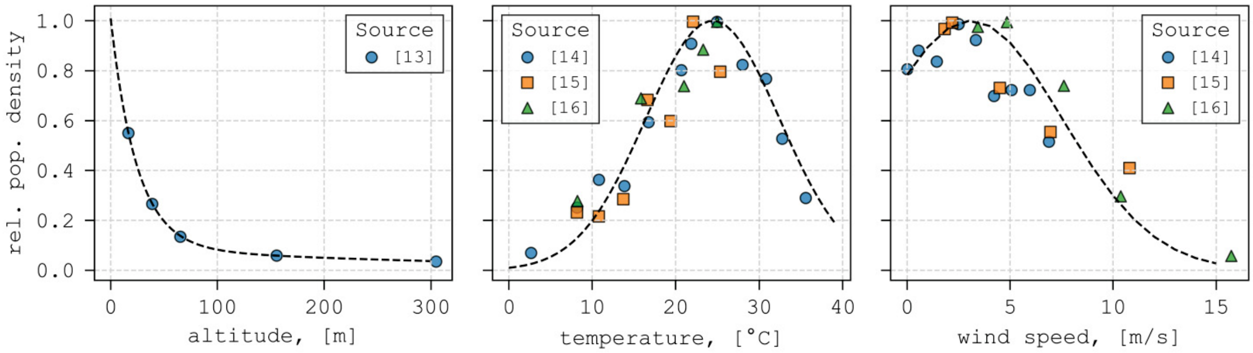

Figure 6: Relative insect population density with respect to altitude, temperature and wind speed. Data sources provided in respective legends.

3.1.3. RESULTS

The impact of the insect contamination on overall aircraft level depends on various operational boundary conditions. Besides the obvious parameters such as the number of flight cycles per year or the global network flown, the resulting laminar effectivity also depends on the cleaning interval assumed. The optimal cleaning interval varies with the occurrence of natural cleaning (e.g. rain), the cost for cleaning labor and material as well as the fuel cost (to determine whether it is worth cleaning or not) and is out of scope for the present challenge. For further information on this relationship, refer to the analysis and optimization presented in Ref. [17].

The overall average of laminar effectivity drops from 100% with no insects to somewhere between 75 and 92%, depending on the underlying cleaning interval. The results are summarized in Table 1 and assume a natural cleaning. For both shown missions, the interval of *every other day* (i.e. every second day) seems to be a good compromise on a first glance.

Table 1: Resulting average laminar effectivity with varying cleaning intervals

Cleaning Interval	Average laminar effectivity	
	Design Mission	Avg. Mission
no cleaning	75%	77%
every month	76%	78%
every week	78%	79%
every other day	**85%**	**86%**
every day	91%	90%
every flight	91%	92%

3.2. SETTING PRIORITIES (HLFC-WIN)

The industrial and research partners in HLFC-Win are currently working together to reach TRL2. This may seem somewhat surprising since HLFC has been under investigation for some decades now and has reached higher TRLs in other projects. However, HLFC-Win aims to design and develop a highly integrated and efficient wing with HLFC. This requires all partners to rethink the problem and (at least partially) start from scratch. This was done using standard creative product development methods, i.e.:

1. Formulating the overall goal,
2. collecting requirements,
3. formulating functions which fulfil the requirements,
4. analyzing functional interrelations,
5. finding principal solutions using a morphological box and
6. combining compatible principal solutions to overall concepts.

Typically, at this stage the few available concepts contain some rather risky but promising partial solutions with conventional or less risky alternatives as backup solutions. To prioritize one particular alternative over another, it is obviously insufficient to rely on best engineering guesses only. Ideally, this process should rely on quantitative values based on physical or numerical tests. However, these are usually not available at this early project phase. Therefore, the discipline of overall aircraft assessment (OAA) was integrated very early into the project.

3.2.1. ANALYSIS SETUP

Figure 7 illustrates the procedure of having the OAA in the loop. The OAA aims to quantify fuel and cost savings compared to a reference. Its' core is the mission simulation combined with a fast and simple cost estimation. Very often, OAA can be found at the end of an aircraft design loop. By integrating it this early, it is possible to quantify the impact of a certain functional alternative (e.g. bleed air for WIPS) vs. another (e.g. electrothermal WIPS). To do so, a sensitivity study was performed based on the three key parameters for HLFC A/C design:

D: Overall drag reduction (from 0 to 7.5%)
M: Total mass increase (from 0 to +4500 kg)
P: System power offtakes (from 0 to 300kW)

Both the payload and range were held constant at 31.5 tons and 3000 NM[6], respectively. As the performance of the reference aircraft (namely XRF1) was not available for the moment, an alternative was needed. A similar sized aircraft (i.e. an Airbus A330) was thus used and slightly modified to match the performance of the XRF1 at the design and average mission. Nevertheless, it can be assumed that the relative sensitivities are representative enough at this stage.

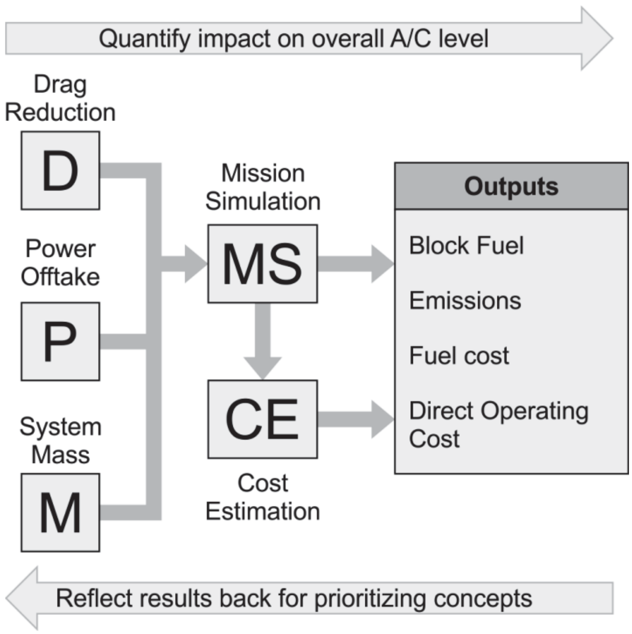

Figure 7: Illustration of the overall aircraft assessment in the loop

The overall goal of the sensitivity analysis is not only to quantify the impact of a change of one parameter on A/C performance level, but also to be able to compare this with respect to the change of another parameter. To put this into an example, questions of the following kind should be answerable: If a particular concept alternative shows to be more lightweight but has a higher power offtake, should it still be preferred over the base concept?

3.2.2. RESULTS

The results of the sensitivity study are given in relative block fuel reductions and are multidimensional, i.e.:

$$\Delta F_B = f(x_1, x_2, x_3) = f(D, M, P)$$

The used two-dimensional visualizations shown in the following figures are therefore given with one parameter held constant (highlighted at the top right corner), i.e.:

$$\Delta F_B = f(x_1, x_2) \qquad \text{with } x_3 = \text{const.}$$

[6] Which corresponds to 300 passengers @105kg and the average flown distance by airlines

Figure 8 shows the impact of drag reduction (abscissa) and additional system mass (ordinate) on the block fuel changes. Negative values on the contour labels denote fuel savings compared to the reference, whereas values greater than zero show increased fuel consumption. The sensitivities themselves can be quantified (at least pointwise) by measuring the required change of each parameter to reach the next contour line. For the point shown, an additional drag reduction of about one percentage point is needed to improve the fuel savings from 1% to 2%. Alternatively, the system mass has to be reduced by roughly 2.2 tons.

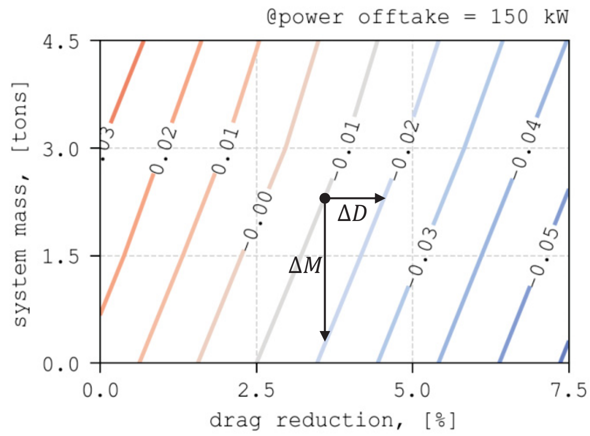

Figure 8: Sensitivities of block fuel savings towards drag reduction and system mass

In the same way, the sensitivity towards power offtake parameter can be compared to the sensitivity towards drag reduction. In this case, the one additional percentage point in drag reduction has the same block fuel impact as a decrease of 100 kW in power offtake, see Figure 9.

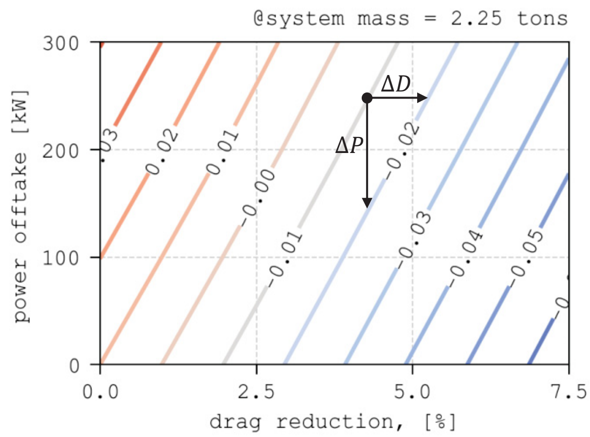

Figure 9: Sensitivities of block fuel savings towards drag reduction and power offtakes

When comparing power offtake and system mass directly, as shown in Figure 10, the example question at the beginning of the section can be answered. If the lightweight alternative requires additional 100 kW of power, the overall mass savings have to be greater than two tons.

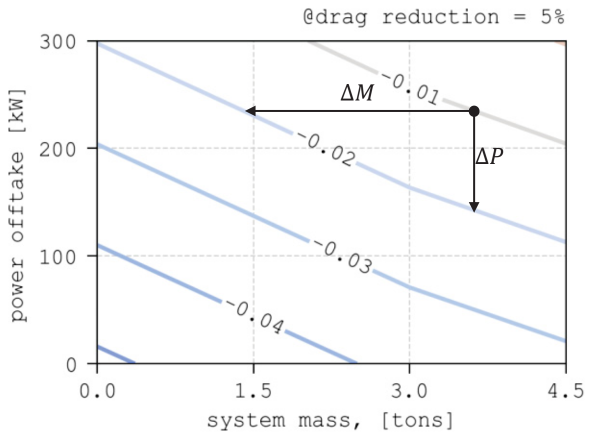

Figure 10: Sensitivities of block fuel savings towards system mass and power offtakes

The mentioned sensitivities are strictly speaking valid for the shown points only. However, these values are quite representative as the fuel savings behavior is mostly linear throughout the analyzed range.

The following table provides another point of view on these sensitivities, which has shown to be easily understandable by each discipline. It summarizes the equity of a change of each parameter by one unit step in the other parameters. So, in layman's terms, a penalty of 1 kW power offtake is roughly as "bad" as a penalty of 20 kg system weight (on average). Additionally, the last row monetarizes these sensitivities in fuel cost savings assuming 500 flight cycles per year and $3/gal for the fuel price.

Drag reduction 1 % is equal to	**Power offtake** 1 kW is equal to	**System mass** 1 kg is equal to
Ø110 kW (P)	Ø0.009 % (D)	Ø0.0004 % (D)
Ø2300 kg (M)	Ø20.3 kg (M)	Ø0.047 kW (P)
Ø190,000 $/year	Ø1800 $/year	Ø84 $/year

It should be noted that these values have a very preliminary character as they are computed with quite a number of assumptions. These include:

- Drag reduction is applied constantly throughout the mission
- No degradations of any kind are applied
- The aircraft design itself is assumed to be appropriate and consistent for all parameter combinations

However, these values may be used to get a tendency for prioritizing one concept over one another.

4. CONCLUSION

The present paper provides a snapshot of the current work of two Clean Sky 2 projects dealing with Hybrid Laminar Flow Control from an overall aircraft assessment point of view. The aim of the first project, called ECHO, is to apply HLFC to the horizontal tailplane of the current Airbus A350 in a certifiable and cost-effective manner. The presented challenge within ECHO dealt with insect contamination and how to quantify its impact from an overall aircraft assessment point of view. Additionally to an updated weather-based insect population density model, a simple methodology for estimating the chordwise accumulation probability was presented. Together with referred accumulation simulation procedures and transfer functions which connect the number of insects with the resulting laminar effectivity, the insect contamination was sufficiently dealt with to pass TRL4. The overall results showed a drop of laminar effectivity between 72 and 94%, depending on operational circumstances such as natural or manual cleaning intervals. The second project, called HLFC-Win, aims to design a wing of a modern long-range transport aircraft with HLFC. In order to develop the most fuel and cost-efficient wing, the project partners decided to start from scratch and tackle TRL2 first. To successfully pass this gate, it has to be shown that the key problems have been understood and the pinpoints have been identified. The consortium then has to develop multiple concepts fulfilling all requirements. To guide the disciplines and partners throughout this concept selection phase, the three impact of the key parameters *drag reduction (D), mass increase (M)* and *power offtake (P)* have been varied to analyse the fuel burn sensitivity towards them. Results revealed a tremendous sensitivity towards *(D)* in percent, a high sensitivity towards *(P)* in kilowatts and a low sensitivity towards *(M)* in kilograms. The quantified values will be used for upcoming trade studies between two or more concepts and thus form a basis for successfully passing TRL2 and higher.

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