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Article

On how to consider climate change in aircraft design

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Abstract

The increasing knowledge in atmospheric sciences and modelling has started to enable the assessment of the contribution of aviation to climate change. Aeronautical engineering therefore has to consider explicitly Earth's atmosphere in future aircraft design. Aviation being a complex business with many different stakeholders, both configurational and operational design solutions for minimum atmospheric impact have to be evaluated for real flight operations. This paper presents a methodology providing a systemic structure for such evaluations. An exercise on two-stage operations with an existing longrange aircraft type is used to illustrate this methodology incorporating some major operational effects. Despite various limitations, the methodology highlights the fact that, in a global operational context, there remains a large gap between theoretical benefits and actual performance.

Zusammenfassung

Fortschritte bei der Erforschung der Atmosphäre und ihrer Modellierung erlauben in jüngster Zeit die Bewertung des Beitrags von Luftverkehr zum Klimawandel. Aufgabe der Luftfahrtingenieure ist es nun, diese Erkenntnisse explizit im Entwurf zukünftiger Flugzeuge zu berücksichtigen. Die Luftfahrtbranche ist jedoch ein komplexer Wirtschaftszweig und muß viele unterschiedliche Interessen bedienen. Technische Lösungen für minimalen Atmosphärenschaden sowohl seitens der Konfiguration eines Flugzeugs als auch seitens seines Betriebs müssen in Bezug auf ihre Eignung im wirklichen Flugbetrieb überprüft werden. Die hier beschriebene Methodik stellt dazu einen systemischen Überbau bereit. Veranschaulicht wird die Methode anhand eines Fallbeispiels zum Betrieb eines existierenden Langstreckenflugzeugs mit Zwischenlandung, wobei einige wichtige operationale Auswirkungen berücksichtigt werden. Trotz gewisser Einschränkungen zeigt die Methodik auf, dass oft eine große Diskrepanz zwischen theoretischem und praktischem Nutzen technischer Lösungen im weltweiten Flugbetrieb besteht.

1 Introduction

Civil aviation is confronted with increasing public attention concerning its impact on the environment. Whereas noise has been the principal cause of anxiety since the early years of commercial air transport, air quality around airports and climate change have only been considered more recently. The aviation business is very complex, since many different stakeholders – authorities, air traffic control (ATC), airlines, airports, aircraft and engine manufacturers – have to satisfy their respective needs and contribute to a safe and economic means of transport for leisure and business passengers.

When it comes to reducing the aviation's environmental impact, each of the contributors is asked to evaluate his part of the story and to undertake any reasonable effort of mitigation. Aircraft and engine manufacturers have achieved large increases in fuel efficiency over the last decades, which, apart from the economic interest, have reduced the environmental impact. Today, it appears that other stakeholders still have large potentials to further mitigate the impact of aviation on the environment. According to Lufthansa German Airlines, ATC improvements could allow for a reduction of 8 % to 18 % of fuel consumption over Europe and, military airspaces still cause substantial deviations leading to a higher fuel burn (LUFTHANSA, 2006). Yet, reducing the impact on climate change still remains a task of the aircraft designer.

The contribution of aviation to climate change was estimated at around 3.5 % of the global anthropogenic radiative forcing for the year 1992 in the IPCC Special Report (PENNER et al., 1999). A more recent estimation from the EU project "TRADEOFF" gave a similar total forcing from aviation for the year 2000 despite the increase in traffic, which was due to a downgrading of the importance of line-shaped contrails. The radiative forcing from contrail-induced cirrus, however, is supposed to be potentially as high as the sum of the other contributions (SAUSEN et al., 2005).

The impact on climate change is determined by the quantity, type and location of engine exhaust gas emissions. These parameters are mainly, though not exclu-

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sively, determined through the design of an aircraft and its engine. Whereas non-optimal flight routing, holding patterns and other extra-fuel-consuming events are difficult to account for in aircraft design, as they are difficult to predict, the scheduled flight network is well defined and can therefore be interlinked with the design process for new aircraft (i.e., along with other parameters such as need for specific ranges and/or capacities). This linkage is particularly important when it comes to evaluating the atmospheric impact of an aircraft concept.

The methodology presented here provides a systemic superstructure for the evaluation of the impact on the global atmosphere of an aircraft concept, embedded in global operations, and thus prepares for its optimisation for minimum contribution to climate change. The methodology does not take into account other environmental effects such as noise, local air quality, occupational health and environmental impacts during the production of aircraft. It focuses on effects of aircraft operations on a global level, i.e. on climate change. As a concrete example for “atmosphere-compatible” design approaches, two-stage operations are assessed in this regard. This example will also highlight operational implications of such approaches for “environmentally friendly” aviation.

2 Relevance of the environment in aviation

The protection of the environment has influenced the development of the aviation system for a long time. In the public arena, aviation is well appreciated as a convenient, inexpensive, safe and primarily fast means of transport, by business and tourists on the one side, strongly analysed and criticised by airport neighbours and environmental organisations on the other side. Aircraft have become far more fuel-efficient during the last decades through advances in lightweight structures, the reduction of aerodynamic drag and more efficient jet engines. Emission indices of nitrogen oxides (NO_x) have been and are still being further reduced with innovative combustor concepts and heat exchangers etc. (EGELHOFER, 2006). As fuel contributes to a significant extent to aircraft operating cost and as fuel prices continue to increase, the reduction of fuel consumption remains a major concern for future aircraft. Along with decreasing fuel consumption, carbon dioxide emissions are reduced proportionally. Carbon dioxide being an important contributor to the greenhouse effect, the impact of an individual aircraft on climate change should thus continue to be reduced in future, even if the impact of other exhaust products needs to be evaluated in addition.

However, it is not the aircraft itself, but its operation that has an environmental impact, so that the aviation system as a whole needs to be considered when evaluating the atmospheric impact of an aircraft concept. Many different stakeholders have an impact on the “production” of each flight. See Figure 1 for just some examples.

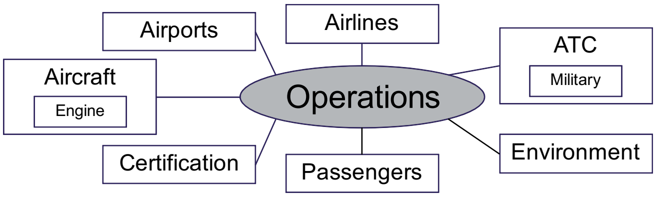

Figure 1: Some of the most relevant stakeholders of aviation, who have an influence on the operation of commercial aircraft.

The consideration of climate change in aircraft design turns out to be a complex task as no only does it involve the aircraft and engine manufacturers, but also airlines (business models, fleet planning), airports (capacity, traffic management, environmental restrictions), Air Traffic Management (ATM) and ATC (quality of flight routing, congestion), certification and even the military (restricted airspaces). Passengers are involved both by their personal requirements for a flight (e.g., desire for convenience and speed and environmental consciousness) and by their behaviour during the actual provision of service (e.g., an aircraft has to fly faster to catch up following delays caused by passengers arriving late, and thus consumes more fuel).

Each of the issues referred above is interlinked directly or indirectly with aircraft design. The design engineer then has the difficult task of trying to handle many different and often contradictory requirements, one of which is a minimum contribution to climate change.

3 Design process for minimum atmospheric impact

In current aircraft optimisation loops, noise starts out being integrated as an important requirement, even at preliminary design level. As referred above, emissions are largely minimised in aircraft design through the minimisation of fuel consumption, which also impacts on direct operational cost. An effective evaluation of aviation’s emissions’ impact on the atmosphere is undertaken only after attempting to consider the complete problem and does not apply to a single aircraft type, but rather to the global fleet (see Figure 2). Few projects

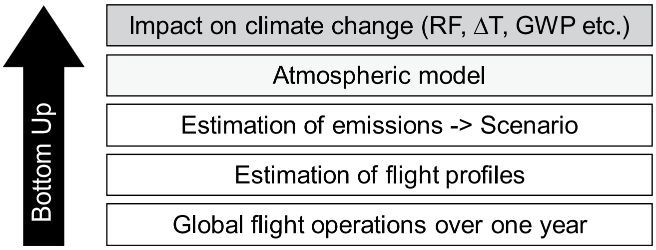

Figure 2: Current evaluation of the atmospheric impact of aviation: bottom up method. No feedback to aircraft design.

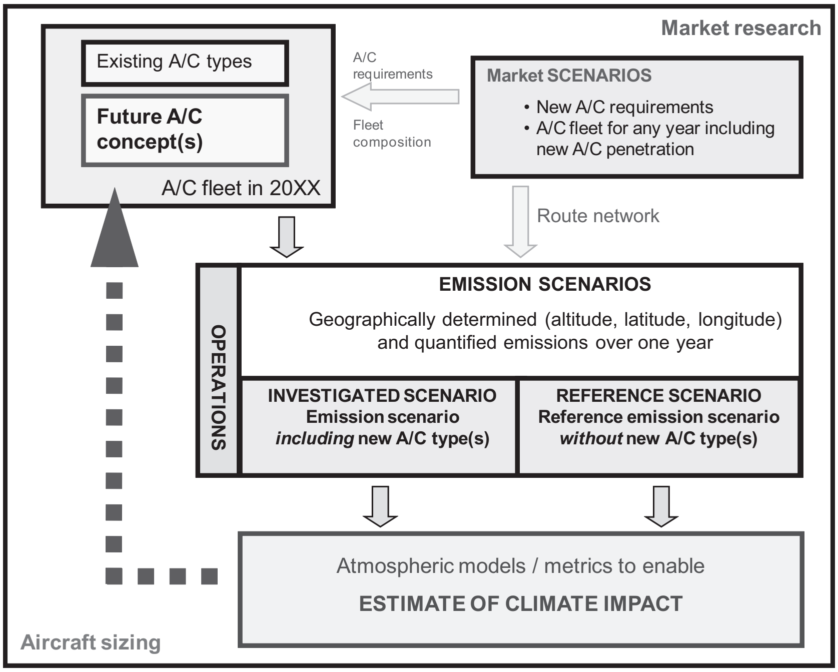

Figure 3: Design approach for minimum atmospheric impact, with feedback to aircraft design. Future aircraft designs are embedded in a global fleet. Market scenarios help defining future requirements for aircraft and traffic demand. Operations are simulated in order to build up detailed emission scenarios, one with and one without the aircraft to be investigated. Upon these results, an atmospheric metric shall allow assessing the environmental impact of the considered design changes and feed back into the initial design study. The methodology aims at aircraft design for minimum atmospheric impact.

such as TRADEOFF and SCENIC have performed such a study to its full extent (TRADEOFF final report: Isaksen et al., 2003; several publications from SCENIC in preparation). This activity is now pursued in the European project QUANTIFY (www.ip-quantify.eu). Other projects stop at the level of emission scenarios that are then provided for consecutive research (AERO2K project, see Eyers et al., 2004). Such complex emission scenarios represent the real emissions in the utmost precision for past years, and good estimates for future years. Such an approach is important to provide a sufficiently reliable representation of the global situation in terms of pollution and the consequent possible climate change in order to enable necessary political action to be taken. If wanting to consider climate change in the design of future transport systems, and more particularly in that of future aircraft, such an estimate of the climate change impact must be extremely simplified and made flexible so that aircraft design options can be weighed against each other in terms of their climate impact, still keeping a sufficiently reliable global picture not to falsify results.

Our approach (see Figure 3 and Egelhofer, 2006) embeds a new aircraft concept in a global fleet on a real route network. With a market forecast and aircraft performance data, global emission scenarios are created. This process enables the assessment of the various operational adaptations such as new flight altitudes or speeds, which will result from the new aircraft concept. For the subsequent evaluation of the impact on the atmosphere, some atmospheric metrics and modelling will be included in the process as soon as these are available. This could be, e.g., Radiative Forcing, Global Warming Potential and Global Temperature Potential (see Shine et al., 2005, and Berntsen et al., 2005). A sufficient reliability of the metrics is a prerequisite for their confident integration into the design process. Varying aircraft parameters of the investigated aircraft concept enables a comparative study between the resulting emission scenarios and their respective atmospheric impacts.

For the application of the methodology for new aircraft, data for the future global fleet have to be estimated, which necessitates sound support from market research. The comprehensive character of the approach makes a proper organisation and setting up of parameters and methods essential. The precision levels of all modules have to be reasonably aligned and the consistency of the data has to be guaranteed. Not only does a real integration in aircraft design of the impact on climate change enable its evaluation or minimisation, but it also enables tradeoffs with noise and local air quality, that tend to foster other design solutions. The approach aims at contributing to a reasonable compromise of design parameters for economically viable, environmentally friendly and thus sustainable aircraft. At its current maturity level, despite immediate limitations, the methodology can already give some useful results and

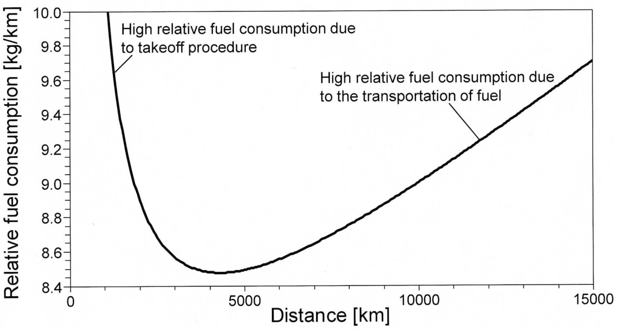

Figure 4: Relative fuel consumption in kg/km for an example longrange aircraft, depending on the distance flown. Calculated based on optimised mission profiles for each distance, with an average load factor. Data from Airbus.

these presage an effective influence on the aircraft design process.

4 Two-stage operations as example of use of the methodology

For illustration of the methodology presented in section 3, a very simplified example study was conducted. For this purpose, two-stage operations on an existing longrange aircraft type were chosen. The same methodology could also be applied to additionally reflect configurational advances in aircraft design.

The market basis (see Figure 3) is drawn from data from the Official Airline Guide (OAG) for the year 2005. For the time being, fuel burn (proportional to CO_2 and H_2O emissions) was chosen as metric for the impact of aviation on climate change, as not other appropriate atmospheric metric or model was available to the authors. This procedure does not fully exploit the methodology such as presented in section 3, but illustrates its potential capacity.

In steady flight, the thrust of an aircraft is equivalent to its drag, much of which is directly linked to the aerodynamic lift of the aircraft. Consequently, an increased aircraft weight demands more thrust and leads to higher fuel consumption. On longrange flights, aircraft use a lot of fuel just to transport fuel, which leads to a high relative fuel consumption on very long distances. On the other hand, the takeoff procedure is very fuel-consuming, which leads to high consumption on short routes. For each aircraft, a distance for minimum fuel consumption per flown kilometre can be determined. In the example given in Figure 4, the optimum stage length is 4300 km.

An approach to reducing the fuel consumption for longrange flights is to separate the flown distance into two or more stages ("two-stage operation" or "multi-stage operation"), of which each length should be as close as possible to this minimum.

4.1 Theoretical fuel reduction potential with two-stage operations

If the distance to be flown is only slightly longer than this optimum stage length (4300 km in our example), a two-stage operation may not save fuel, as the fuel-consuming takeoff procedure would then weigh heavier than the saving by not "transporting fuel". The curve plotted in Figure 4 can be approached by a function of the type

$$y = ax + b + \frac{c}{x} \tag{4.1}$$

where x is the distance to be flown and y is the relative fuel consumption per flown kilometre. The parameters a, b and c are chosen such that the curve is best estimated for stage lengths above 300 km and under 12,000 km. Note that longrange aircraft do fly some very short sectors. The potential relative fuel saving Δy of a two-stage operation is

$$\Delta y = y_{total} - \frac{y_1 \cdot x_1 + y_2 \cdot x_2}{x_{total}} \tag{4.2}$$

where x_1 and x_2 are the lengths of the two stages, y_1 and y_2 are the respective relative fuel consumptions of the two stages and x_{total} is the total distance with a total relative fuel consumption of y_{total}, if flown in one flight. Considering that $x_{total} = x_1 + x_2$ and equation (4.1), we get

$$\Delta y = 2ax_1 - \frac{c + 2ax_1^2}{x_{total}} \tag{4.3}$$

Dividing (4.3) by (4.1) gives the potential fuel economy ratio e:

$$e = \frac{-2ax_1^2 + 2ax_1x_{total} - c}{ax_{total}^2 + bx_{total} + c} \tag{4.4}$$

Table 1: Theoretical maximum fuel economy operating in two stages on a great circle route, with an existing longrange aircraft, and respective fractions of flights and available seat kilometres (ASK) of the global traffic of aircraft with more than one hundred seats.

Theoretical fuel economy	Distance greater than [km]	Fraction Flights	Fraction ASK
0 %	6100	4.2 %	37 %
1 %	6600	3.4 %	32 %
2 %	7200	2.7 %	27 %
4 %	8700	1.5 %	17 %
6 %	10,300	0.43 %	5.5 %
8 %	12,300	0.05 %	0.5 %

Plotting function $e(x_{total}, x_1)$ shows for which total distances and which partial distances considerable fuel savings can be obtained, if operating as two-stage operation (see Figure 5).

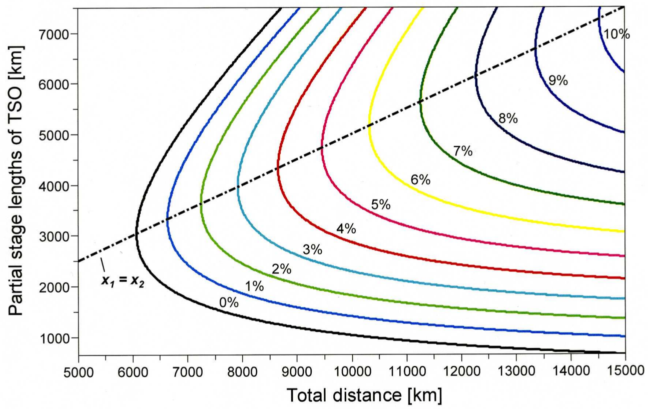

Figure 5: Theoretical fuel economy for an example longrange aircraft with two-stage operations in percent (isolines), depending on the total distance (abscissa) and the lengths of the two stages with two-stage operations (ordinate). The dash-dotted line gives the respective optimum stage length ($x_1 = x_2$).

4.2 Market share of routes capable of two-stage operations

Considering, e.g., a fuel saving of 2 % “interesting”, routes of more than 7200 km would be worth a two-stage operation with the considered example aircraft. In the global air traffic (OAG data from 2005), such flights represent only 2.7 % of all annual flights by aircraft greater than one hundred seats, but 27 % of available seat-kilometres (ASK) (see Table 1). Multiplying these 2 % with 27 % gives around half a percent of fuel saving as a very rough estimate (considering global ASK and fuel consumption percentages proportionate). The maximum theoretical fuel economy with this example aircraft would be attained if operating it on all routes above 6100 km (corresponding to a positive fuel economy) at the respective optimum stage length ($x_1 = x_2$). Despite the high fraction of routes “capable of a two-stage operation”, i.e. with positive fuel economy, this would still only account for around one percent of the global fuel consumption of aircraft with more than one hundred seats. The estimate is based on the following equation, where E_{global} is the total theoretically attainable fuel economy with our example aircraft for the global traffic:

$$E_{global} = \sum_{Distances \geq 6100\,km} \Delta Fraction\ ASK_{Distance} \cdot e_{Distance} \tag{4.5}$$

Optimised flight plans with the respectively best aircraft type on each route would lead to higher economies. On the other hand, the consideration uses the optimum stage lengths ($x_1 = x_2$), which in most cases is not achievable on realistic flight paths. Additionally, total flight distance will lengthen as intermediate airports are not necessarily available on the great circle between departure and arrival point. This estimate gives an idea of the order of magnitude of the fuel saving to be attained without changing the aircraft design.

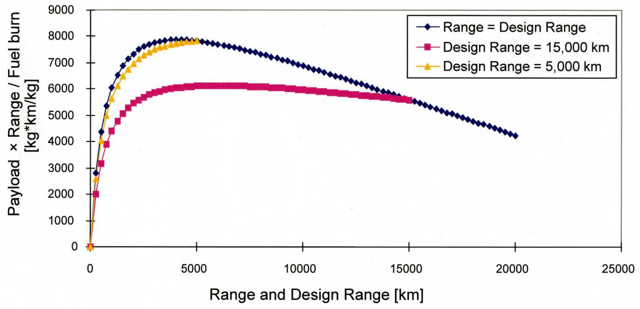

Figure 6: Variation of payload fuel efficiency with range and design range: swept wing kerosene-fuelled aircraft (from GREEN (2005), arranged by SCHNIEDER and HYDE (2006)).

4.3 Theoretical reduction potential with redesigned aircraft

Assuming that it would be viable to have such types, a higher potential for savings could be attained, if aircraft were designed for shorter ranges. The smaller fuel quantities needed would allow a lower structural weight of the aircraft. A lighter structure again leads to reduced fuel consumption (see 4.1), which feeds back into a reduced structural weight. According to GREEN (2005), an aircraft designed for 7400 km operating in stages on current real routes would save 10 % in fuel burn compared to an aircraft designed for 14,800 km. Compared to 4.1, this estimation allows for real routes, but still is not representative for the global traffic, but only for one longrange aircraft type, just as in our study. For comparison, our example aircraft would provide around 10 % of fuel saving operating in two equal stages on a total distance of 14,800 km without being redesigned. Pushing this theoretical approach to its extreme, optimising range and seat capacity at the same time would lead to much higher savings. As shown in Figure 6, the payload fuel efficiency of an aircraft designed for 5000 km on a 5000 km leg, and furthermore assuming optimum seat capacity, would exceed the one of an aircraft designed for 15,000 km by almost 30 %. This benefit remains theoretical, as aircraft cannot be designed specifically for each needed range, neither for each seat capacity. However, since this paper was presented, Green has corrected his calculations and his theoretical estimates of the percentage are even greater (GREEN, 2006).

As explained in section 4.1., these theoretical gains for one single aircraft or route sum up to a few percent only when put into perspective of the global route network. For comparison, an Airbus internal study estimated the fuel saving benefit of two-stage operations at 2.6 % on a global (commercial aircraft greater than one hundred seats) level (SCHNIEDER and HYDE 2006), already taking into account some of the major drawbacks (see section 4.5.).

4.4 Impact of two-stage operations on climate change

With the fuel saving, the masses of products of combustion CO_2 and H_2O emitted into the atmosphere are reduced, and so also their direct effects on climate. The potential impact of other pollutants, especially of nitrogen oxides, is more uncertain as it results in a combination of two effects that can be contradictory: the reduction of emissions and their radiative effects by fuel saving, and the increased production of emissions at lower altitudes. Today large uncertainties remain concerning the positive/negative impact versus small vertical fluctuations at these altitudes. Given the lack of reliable metrics, only studies with atmospheric models can evaluate the potential benefit appropriately.

Another consequence of emissions is the formation of condensation trails, or contrails, and their persistence when particular atmospheric conditions (supersaturation with respect to ice) occur during the flight; these contrails contribute to increased radiative forcing as they have similar effect as natural clouds. The potential impact of two-stage operations is very uncertain, as the atmospheric conditions depend not only on the altitude, but also on latitude, season and time of day of a flight. Once again, only studies with atmospheric models can estimate their radiative impact. And in that case, the used traffic scenario would need to break down flight operations not only to their location, but also to their exact timing (hours, or at least daytime).

If the two-stage operations tend to reduce fuel consumption during the flight, their application will also increase the number of landing and takeoff (LTO) cycles in the airport areas. As a direct consequence pollutants emitted at low altitudes will increase, especially beneath the atmospheric mixing height ($\sim$ 3000 ft). Two species are more particularly concerned: nitrogen oxides NO_X and particles. For local air quality preservation, requirements from local authorities might limit air traffic, for example by fixing annual LTO movements or a quota of permitted emissions per source (see EGELHOFER et al., 2006). It is possible to make design tradeoffs that lead to a reduction of the emissions of NO_X during takeoff, with some potential penalties for fuel consumption at altitude as these tradeoffs influence directly the engine design. This type of environmental measures could impair the initially assumed benefit of two-stage operations.

A profound assessment of the benefit of two-stage operations for environmental impact would presume the integration of a reliable atmospheric model or metric in the loop.

4.5 Operational involvements and economic interest of two-stage operations

The potential fuel savings presented in chapters 4.1 to 4.3 are theoretical. Several aspects would counteract the benefit of two-stage operations:

- Availability of appropriate airports: Even if an airport was available near the mid-range of a certain route, it is not sure it would be able to handle additional traffic, and that it has the necessary infrastructure (runway strength, fuel supply, navigation aids etc.).
- Maintenance cost and higher fatigue of the pressure cabin due to the higher number of flight cycles
- Additional landing and takeoff cycles affecting local air quality (see 4.4) and noise concerns, especially important at busy airports
- Organisational effort for airlines: crew management, airline subsidies at mid-way airports
- Less flexibility for airlines to choose routes, if aircraft are designed to lower ranges
- Value of time for the passenger: A full landing and takeoff cycle with refuelling takes one to two hours, which might not be acceptable for many passengers, those with children, the old and those paying high ticket prices (business passengers). One hour for 300 passengers would then cost up to 15,000 Euro based on standard values recommended by EUROCONTROL (2005). However, these numbers are based on just one study out of several. The confidence in such numbers is thus very limited.

The economic interest of two-stage operations, justifying the effort of severe modifications of the aviation system, is impacted by all of the aspects mentioned above. Two-stage operations are interesting and applicable on specific routes only, but cannot be considered a generally fuel- or climate impact- reducing measure today. An expansion of such operations would presume substantial adaptations in the aviation infrastructure, especially at airports. In the end, the overall benefit of two-stage operations depends essentially on the fuel price and wider economics.

As indicated above, the methodology presented in this paper could be used to assess both operational and configurational advances in aircraft design and indicate the true viability of new aircraft types and the effects on the aircraft fleet.

5 Summary and conclusion

A methodology to consider the impact on climate change in aircraft design was presented. As an example, two-stage operations illustrated the interest in a systemic view of aviation in this regard. Their benefit in terms of reducing climate change was roughly estimated. The approach highlighted the discrepancy between purely theoretical considerations and real flight operations. It was shown, that it is difficult to sufficiently reproduce the aviation system in order to assess its contribution to climate change, and to moreover consider those effects in aircraft design.

For the evaluation of the benefit of a new approach in aircraft design and operations in terms of climate change, it is necessary to have a good overview of both the different stakeholders of aviation and the impact of aircraft engine emissions on the atmosphere. The methodology presented here is an approach to allowing for the equitable consideration of aircraft design, market requirements, operational issues and the atmospheric impact. The interaction between aircraft design and atmospheric impact can then be treated not only "bottom up", but as a fully integrated analysis and optimisation loop.

Increasing the complexity of the studied system and the required competences – from aircraft engineering to atmospheric sciences – takes its toll on the precision of results. In order to get realistic and meaningful conclusions, not only are comprehensive methods needed, but also scientific exchange between the respective specialists' communities. Then the correctness of conclusions – within a given precision – can be reasonably assured. The approach presented here proposes a methodological platform for such an integration of both aircraft engineering and atmospheric sciences. Further examples of application will need to confirm the proposed approach in future.

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