HOLISTIC APPROACH FOR ENVIRONMENTALLY FRIENDLY AIRCRAFT DESIGN

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Keywords: *aircraft design, sustainable aviation, noise, local emissions, global emissions*

Abstract

The objective of this study is to analyse how the impacts of aviation on the environment interact and to conceive new strategies in aircraft design that might reduce these impacts while duly considering economic constraints. The environmental impacts this study focuses on are atmospheric, local air and noise pollution. A single event and multiple event approach are elaborated to enable an economic evaluation of the respective aircraft design changes concerning their environmental impact.
A complete list of abbreviations is given at the end of the paper.

1 Introduction

Aviation has always been linked to the industrial development of societies. Today, especially Asian countries are establishing fast growing air transport systems and many new airports have been built recently to comply with the large increase in air traffic demand (e.g. Kansai, Hongkong, Centrair, Incheon). But also in Europe and the United States, aviation keeps growing at considerable rates. Along with the development of the air traffic industry, environmental concerns increasingly raise public interest.

Aircraft noise has been tackled for a long time by technological and procedural advances that have considerably decreased its extent and impact. These positive effects are yet often outweighed by the increase in air traffic, so that the issue remains a major challenge for future aircraft and operations.

Aviation emissions of pollutant gases have been decreasing by increased aircraft fuel efficiency for a long time[1]. Their environmental impact has been dealt with explicitly only recently, although major pollutants have been regulated by the International Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) since 1981 [1].

The general public easily perceives aircraft noise, not so much local emissions that are relevant for local air quality, and even less the impact of aircraft emissions on climate change. Still, all three domains are of great social, political and scientific importance. To increase the environmental compatibility of aviation, none of the three must be compromised. Meeting the environmental challenge successfully is a prerequisite for sustainable aviation.

The Institute of Aeronautical Engineering of the Technical University of Munich is currently establishing a holistic consideration of aviation's environmental impact, including procedural, technological, political and economic aspects of noise, local and global emissions. In a first step, this paper aims at elaborating how these environmental implications can be equitably taken into account in **preliminary aircraft design of commercial aircraft**. Different participants of the aviation system have appropriate options to contribute to environmental control (e.g. ICAO Balanced Approach to Aircraft Noise Management [2]). In the sense of this analysis, we focus on the aircraft respectively the aircraft manufacturer and their reduction

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[1] However, highly fuel efficient engine technologies have led to a relative increase of nitrogen oxides emissions [3].

possibilities. Relevant interdependencies with other domains of the air traffic system will be addressed along the way.

2 Environmental Impact of Aviation

Aviation has an impact on the environment due to its noise and pollutant gas emissions. Referring to their respective effects, engine exhaust gas emissions are treated as 'local', when occurring around an airport, and as 'global' emissions for their influence on the global atmosphere, thus including the entire mission (Fig. 1).

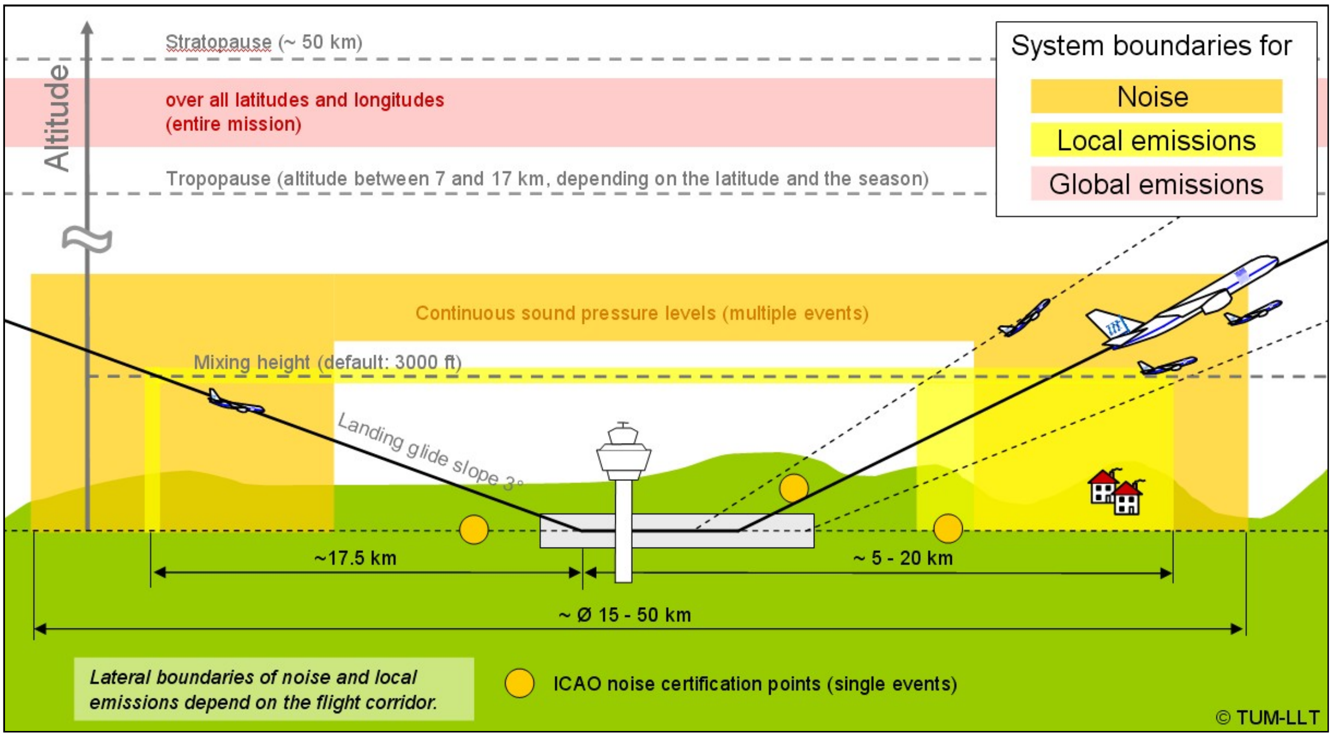

Fig. 1. Environmental impacts of aviation – system boundaries. The given shaded boundaries for noise, local and global emissions were estimated based on studies conducted at LLT. The limits of the system boundaries of noise impact depend mainly on the number and size of aircraft flying, and the defined cumulative noise level threshold, thus the lower limits refer to airports with few operations or permissive noise protection. For comparison, the ICAO noise certification points are added to the diagram. Local emissions are bordered by the atmospheric mixing height, which results in a precise distance for the approach, and a fairly broad range at take-off due to the difference in climb angles. Global emissions concern the entire mission and are only confined by the cruise flight altitudes (lower part of the stratosphere). In the medium and long term, they stretch over the whole planet.

2.1 Noise

The term 'aircraft noise' refers to the **generation**, **propagation** and **impact sound** created by the operation of aircraft. The human reaction to aircraft noise is very subjective and emotional and does not only depend on numerous acoustic aspects (aircraft type, operations), but also on non-acoustic factors (personal attitude, mood) [4], [5]. Noise perception varies according to the background noise level and local habits. Due to this variety and the logarithmic scale of noise, a comparative statement relating to other sources is difficult. However, there is enough scientific evidence to prove that exposure to aircraft noise can lead to adverse health effects and deteriorate the quality of life of residents. The following list gives an overview of the most important extra-aural effects (aural effects are unlikely due to civil aviation):

- **stress-related long term health effects**: hypertension, cardiovascular diseases like angina pectoris, hormone regulation, biochemical effects
- **psychosocial effects**: annoyance, effects on psychosocial well-being, psychiatric disorders, psychiatric hospitalization and behav-

ioural responses (adaptation, complaints and community reaction)

- **sleep disturbance**: awakenings, changing of sleep levels and patterns, subjective quality of life
- **effects on performance** (especially examined for children at school in terms of attention, memory capability and motivation)
- **direct speech and auditory task interference**

These effects have been analysed with a varying level of detail in several studies since the 1970s [6][7][8]. According to [8], annoyance, hypertension (inconclusive), ischaemic heart disease, speech interference and sleep disturbance are based on a sufficient database to derive significant dose- response relationships. These causal dependencies are normally related to continuous sound pressure levels (L_{DEN}, L_{DN}, L_{EQ}) as a function of different observation thresholds: for example the high 70 dB L_{DEN} level for hypertension and heart disease and 50/55 dB L_{DEN} for annoyance in some papers. Alternatively, they can be referred to or even combined with single event descriptors (SEL, L_{AMAX}), which are more sensible for short time exposure.

2.2 Local emissions

Emissions from aircraft are generated by the engines, the APU as well as the brakes and tires which emit particles through abrasion. The engine exhaust plume mainly consists of the emissions CO_2, H_2O, NO_x (NO, NO_2), HC, CO, SO_2, Benzene and particulate matter (PM).

Apart from CO_2, all aircraft emissions have an impact on human health and the natural environment in the vicinity of an airport. Currently, the most publicly discussed pollutants are PM_{10}[2] and NO_2. PM_{10} increases the rate of lung cancer and affect plant growth and materials, which induces economic and social cost. NO_2 is considered to cause troubles like chronic bronchitis and other respiratory diseases [9]. Furthermore, NO_2 has toxic effects on plants and triggers acid rain leading to acidification of soil and water as well as to corrosion of metal and stone.

HC and NO_x are the most important ozone precursors in the ground layer, which is responsible for summer smog. Ozone affects the respiratory system, causes dizziness and may even kill [10].

As cancer is caused by benzene and particles, national institutions call for an intensification of the national ambient air quality standards (NAAQS). In Germany, for example, the current ambient air quality limits are up to five times higher than the values for an increased cancer risk established by the federal states committee for pollution control [11]. No other aircraft emissions (e.g. SO_2 or CO) are emitted in quantities that would directly affect human health or nature.

2.3 Global emissions

On a global level, engine exhaust emissions of current commercial aviation have an impact on global warming and, negligibly, on the ozone hole, at least with current flight altitudes. With the considerably higher cruise flight levels (e.g. typical supersonic flight altitudes) envisaged, the ozone layer[3] could be harmed significantly [12][13]. Global warming is caused by the emission of greenhouse gases (e.g. CO_2, H_2O, O_3), aerosols or clouds, that disturb the Earth's radiative balance. This perturbation is called 'Radiative Forcing' (RF) and measured in mW/m^2. RF is currently the most widespread metric for the description of climate change. The share of aviation in anthropogenic global warming was estimated at 3.5 % (corresponding to a RF of ~$50 mW/m^2$) for the year 1992 in IPCC's 1999 Special Report on Aviation and the Global Atmosphere [14] and slightly corrected in the TRADEOFF project [15]. Both reports give detailed values of radiative forcing for each of the pollutant gases.

The following table summarises future consequences of climate change with their respective probabilities according to [16].

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[2] PM_{10}: particles with a diameter smaller than 10µm

[3] The highest ozone concentrations (ozone layer) occur at around 19-26 km altitude.

Impact	Probability
Higher Temperatures	90-99 %
Reduced diurnal temp. range	90-99 %
Increase of heat indices over land (combination of temp. and humidity)	90-99 % over most areas
More intense precipitation events (-> floods)	90-99 % over many areas
Increased summer continental drying and associated risk of drought	66-90 % over most mid-latitude continental interiors
Increase in tropical cyclone peak wind intensities	66-90 % over some areas
Increase in tropical cyclone mean and peak precipitation intensities	66-90 % over some areas

Table 1. Impacts of climate change and respective probabilities for the 21st Century. Summarised from the Summary for Policymakers of [16].

Even if some uncertainties remain as to the extent and the time frame of these changes, climate researchers do converge on the basic results. IPCC will publish new findings on aviation's impact on climate change in its Fourth Assessment Report, due in 2007.

Even if aviation's part in climate change is fairly low today, its high growth rates will further increase the industry's importance in mitigating the extent of climate change. Climate change is considered the most important challenge of the 21st Century [17][18].

2.4 Summary of environmental impacts

The three environmental areas of noise, local and global emissions differ considerably, when it comes to their size and range of impact (human beings, materials, entire biosphere, Earth), public reaction and scientific importance. An objective comparison is further challenged by the difference of system boundaries (see Fig. 1), units and thresholds, local particularities and conflictive requirements. However, such a review stands at the beginning of a coherent consideration of the environment in the design of the air traffic system, which we tried to summarise in the following table.

	Noise	Local	Global
Short term impact	xxx	xx	
Long term impact	x	xx	xxx
Subjective perception	xx	x	
Reactivity of affected people	xxx	x	
Current political attention	x	xx	xxx

xxx = high to x = fairly low

Table 2. Qualitative estimation of the relevance of the environmental impact of noise and pollutant emissions from aviation

This estimation is not so much the answer to the question, but is proposed as basis for discussion. A consideration and trade-off between all three domains must be investigated at preliminary design level and may contribute to lower the overall environmental impact of aviation.

3 Political and Regulative Framework

As a reaction to the various environmental impairments and the consequent sensitisation of major parts of the society, governmental institutions and non-governmental organisations elaborated several regulations, recommendations and policies on different levels: **International** (e.g. 'ICAO'), **Regional** (e.g. European Union), **National** (e.g. 'USA') and single **Airports/Airlines**. Their comprehensive compilation would go well beyond the scope of this paper. Following our research environment and experience, this paper concentrates on German and European legislation. Environmental regulations differ by various parameters (e.g. units, measurement positions, aircraft configurations). They apply to both the initial **certification** of an aircraft and real recurrent flight **operation**s. Yet, those two factors are only loosely related (see Table 3).

3.1 Current certification

ICAO tends to this interest through CAEP and has issued Annex 16 to the Chicago Convention, with Volume I for noise and Volume II for gaseous emissions [1]. Since then, these standards have been tightened on a regular basis. National implementations of ICAO regulations may incorporate slight modifications. These standards apply for new aircraft and do not have to be confirmed in service.

'Chapter 4' of Annex 16 [1] is the current standard of noise certification. The regulation addresses noise reduction at the source by issuing noise limits for single events at three certification points (approach, lateral, flyover; see Fig. 1). In comparison to 'Chapter 3', the limit for the sum of all three values has been reduced by 10 EPNdB. Noise-related aspects of both the aircraft and the flight procedure may have an influence on the noise levels measured.

	Certification	Operation							
		Noise				Emissions			
	Mitigation at source	Assessment and action plans	Land use planning	Operation restrictions	Low-noise procedures	Immission limits	Landing charges	Emission Trading	Fuel Tax
International	ICAO Annex 16 Vol.I (noise); Vol.II (pollutants)								
Regional	↓	Environmental Noise Directive END (2002/49/EC) ↓		Chapter 2 A/C Phase-Out (1992/14/EEC) Chapter 3 A/C Phase-Out (2002/30/EC) with marginal difference to limits (cum. 5EPNdB)		NAAQS (1999/30/EC 2000/69/EC) ↓	ERLIG Recommendation (ECAC 27-4) ↓	Emissions Trading Scheme ETS (closed, open, half-open)	Fuel Taxation System
National	National adaption of ICAO certification (FAA/LBA)		German Aircraft Noise Protection Act (relevant for major airports)			NAAQS (22./33. BImSchV - outside airport area)	Emission Related Landing Charges (national system and local price definition) e.g. Sweden, UK, Switzerland, Germany		
Airport/Airline		Local Noise Action Plan	sound insulation, restriction of new buildings, compensation	e.g. LHR quota, count, curfews, budget	RNAV, CDA at night (LHR, AMS)				

Table 3. Summary of important environmental regulations

Limits for gaseous emissions are issued for NO_x, CO, HC and smoke in relation to an engine's maximum rated thrust in [g/kN] and are calculated for the ICAO LTO cycle [1]. The current standard is 'CAEP/4' with 'CAEP/6', coming into force in January 2007. In contrast to noise, certification is granted not to an aircraft, but to an engine (first individual production model) only and does not consider airframe or installation effects. A specific certification in view of global emissions does not exist.

3.2 Current operational regulations

In line with ICAO, the European Union decided in 1992 to ban regular operations of 'Chapter 2' certified aircraft from 2002. Even if these aircraft were legally certified, growth of air traffic, long life cycles and an increasing difference to state-of-the-art noise levels had necessitated action by aviation authorities. This measure brought noticeable relief for many airports [19]. Comparable measures have been similarly successful in the USA.

The EU published a directive addressing the harmonisation of noise assessment methods and the consequent exchange of information with the public [20]. The document requests periodic noise mapping on large airports with a uniform metric (L_{DEN}, L_{NIGHT}) from 2007, and concrete measures to achieve appropriate noise targets in 2008. A similar approach is being discussed concerning landing fees [21]. Furthermore, a phase-out policy for marginal 'Chapter 3' aircraft has been defined and is documented explicitly at AMS and CDG airports for night time operations [22][23]. Land-use planning and compensation for noise effects was tackled by an 'aircraft noise protection law' in Germany in 1971 [24] and has been revised recently [25].

Where such noise control measures are urgent, insufficient, or missing altogether, noise-concerned airports have developed a suitable noise abatement program (night curfews, quota, operational procedures, landing fees etc.) of their own, taking into account specific local conditions [23].

Operational regulations for gaseous emissions result from local (national or regional) ambient air quality limits that are currently not valid on airport terrain and that are not specific to aviation, but to all sources in the vicinity of the airport. These ‘Air Quality Standards’ concern NO_x, SO_2, PM and apply to short-term periods (hour, day) and long-term periods (annual average) [26][27]. New regional standards and existing national regulations have to be merged (e.g. ‘BImSchV’ [28] in Germany). Such regulations have led to national solo-attempts to establish emission-related landing fees (Zurich airport in 1997, other Swiss airports in 1998 [29]). A European standardisation of the calculation of emission-related landing charges has been recommended by the ‘Emission Related Landing Charges Investigation Group’[4] (ERLIG) [30]. The ERLIG system is based on the total mass of NO_x and HC emitted during the LTO cycle. Sweden introduced emission-related landing charges in 1998 and adopted the ERLIG system in 2004, Switzerland followed in 2005. London Heathrow and Gatwick (UK) introduced an ERLIG-based system in 2004 and 2005 respectively.

Local restrictions concerning the usage of an APU at airports have been established both for emissions and noise control.

3.3 Political attempts for future regulations

On a global level, ICAO discussed different phase-out policies for noise aircraft on a cost-benefit basis, but refused afterwards a general phase-out of ‘Chapter 3’ aircraft in all countries [31]. New certification levels (‘Chapter 5’) have not yet been published, probably because current and future operational regulations established by single airports have become a lot more stringent to aircraft design than the initial certification levels.

It is difficult to give a general view of future noise restrictions at airports due to local specificities in terms of population sensitisation, political reactivity, traffic demand and extension plans. In the long run, it is conceivable that a noise certificate trading comparable to emissions trading might be introduced.

The European Emissions Trading System (CO_2) is supposed to become the central instrument of climate protection in Europe. Air traffic, i.e. all passenger and cargo flights departing from EU airports, regardless of the provenance of the airline, could be included from 2010 [32]. Aviation can be integrated in the ETS as **closed** system (separated from the Kyoto related ETS and favoured by the EU), **open** system (any exchange with other industrial sectors is allowed, favoured by ICAO/CAEP) or **half-open** system (aviation can buy from, but not sell to other industries). [33]

Another instrument for controlling emissions is the taxation of kerosene, which is currently under discussion for all intra-EU flights [34][33]. As such taxes are prohibited by the Chicago Convention on International Civil Aviation, the EU is negotiating with the US to allow unconditional fuel taxation for all airlines.

Ambient air quality limits for NO_2 will be tightened from 2010 and further include ozone and benzene [27][28]. On top of this, the German Federal Environmental Agency insists on introducing an ERLIG-based landing charges system [35]. These issues will necessitate concerted action of all stakeholders at airports.

3.4 Impact of regulations on aviation

Environmental regulations have direct and indirect impacts on several stakeholders in aviation.

Certification provides immediate influence on the aircraft manufacturer, but today is no great incentive for enhancements any more, since modern aircraft easily comply with the respective limits. Yet, operational restrictions (see Table 3) affecting airports and airlines are traced back to the manufacturer and provide now a more relevant design criterion: curfews, movements caps or ambient air quality limits may decrease the capacity of an airport, the aircraft utilisation and fuel consumption (indirect flight paths) of an airline fleet and are thus relevant for their respective operational cost and margin. So do noise or emission-based landing charges and an emission (or noise) trading sys-

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[4] part of the experts group on ‘Abatement of nuisances caused by Air Transport’ (ANCAT) and the the ‘European Civil Aviation Conference’ (ECAC)

tem. This may lead to a (sometimes sudden) decrease in residual value and the premature sale of initially profitable aircraft (fleet renewal). Further cost for aviation stakeholders result from the acquisition, documentation, administration and investigation of noise and emissions data (including complaints around airports). Airports have to cope with resettlements and compensations for heavy noise due to airport protection zones.

Approaches for the treatment of noise and gaseous emissions resemble each other a lot: International certification procedures cover daily operations only partly; regional institutions have developed more efficient environmental constraints and are now harmonising them; where these are not sufficient, local authorities and airports have reacted with even more stringent measures.

The treatment of gaseous emissions is geared by noise, which has been tackled for a much longer time.

4 Aircraft Design and Environment

Designing aircraft is a multi-disciplinary task requiring the parallel optimisation of several interdependent domains such as structures, aerodynamics, flight mechanics, power supply, handling qualities and so on. Apart from technical issues, economic constraints play a more and more prominent role. Considering environmental impacts of aviation as an important driver adds another very complicated and interlinked issue to the already complex aircraft design process. Due to the increasing fuel prices, airlines are now beginning to express their interest in an advanced reflection of environmental impacts.

4.1 Current Approach

Previous attempts to consider the environmental impact early in the design process primarily referred to aircraft noise. Consequently, so-called ‘green aircraft’ are simply noise-minimised aircraft configurations. Formerly, noise benefits were achieved mainly through advances in engine design such as high-bypass turbofans.

As mentioned above, the quantity of pollutant gas emissions has been reduced continuously through improving fuel efficiency. However, the minimisation of the effective environmental harm of aviation’s pollutant gas emissions is taken into account in engine design to meet certification standards, but rarely tightly focused on in aircraft design. Furthermore, the often reciprocal implications of designs for minimum noise and for minimum emissions have not yet been fully explored (Fig. 2).

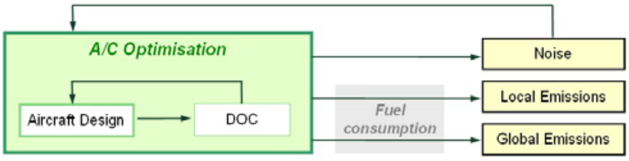

Fig. 2. Consideration of the environmental impact of aviation in the aircraft design process: Noise starts being integrated in the optimisation loop, emissions are integrated via the fuel consumption, but no direct link to their impact on the environment is established.

An approach to treat all three aspects parallelly was presented by Antoine and Kroo [36][37]. Their design process optimises fuel consumption, NO_x emissions during the ICAO LTO cycle and noise (as EPNdB at ICAO certification points) considering direct operating cost. The study showed the feasibility of considering environmental impacts from the preliminary design level and gave first ideas on the respective trade-offs for the considered criteria.

In order to minimise the environmental impact of aviation from a global perspective, a more detailed consideration of the respective effects, such as described in chapter 2, and current and future regulations (see chapter 3) stands to reason. We tried to summarise some of the most important requirements that result from either the impacts or the regulations and should, to our understanding, be taken into account at preliminary design level.

4.2 Environmental Design Requirements From Regulations

Design requirements concerning noise initially were derived from the ICAO certification (see chapter 3.1).

The flight procedure of certification allows only small variations of weights, speed, altitude, minimum cutback altitude and configuration. However, both the airframe and the engine can contribute to combine these parameters optimally in order to undershoot the certification limits as much as possible, be it with or without integrating special technologies (e.g. chevron nozzles). The prediction of airframe noise as a function of aircraft weight, speed, geometry etc. and the integration of engine noise is undertaken at a very early design stage. Precise sound levels are then obtained through measurements.

In contrast to certification, the EU END mentioned above and the various phase-out regulations are not directly relevant for the design of new aircraft as they apply to in-service fleets.

A real design challenge, though, results from local airport regulations worldwide, mostly far more stringent than certification limits. A case often quoted, and maybe the benchmark at the moment, is the London Heathrow quota count system [23] and its impact on the A380 leading to an explicit trade-off between aerodynamics, weight, fuel efficiency and noise impact [38][39]. A second example is the retrofitting of the A318 for steep approach capability at London City Airport (5.5° ILS glide slope for noise abatement) [40].

The certification of gaseous emissions applies to the engines only, so that the design of the airframe is not directly challenged. Indirectly, there is a link insofar as the airlines might choose the aircraft-engine combination that suits best their requirements in terms of gaseous emissions. If, however, the ICAO LTO cycle as basis for emission calculation and certification were replaced by an operational cycle, the aircraft as a whole could contribute to lower the emission level of this cycle. Similarly, both engine and airframe design would be affected by the introduction of the ETS.

Considering the entire aircraft in emission calculation and regulation could drive unconventional designs with higher fuel efficiency (e.g. Blended Wing Body) and low emission combustor technologies, if NO_x are included.

Independently from certification, some airports have introduced excessive operational regulations, where national ambient air quality standards were excessed (e.g. Zurich airport [41]). In order to meet the demand in capacity of these airports, not only engine, but also aircraft design will be further challenged in terms of gaseous emissions.

4.3 Environmental Design Requirements From Impacts

On top of certification-based local restrictions, some more innovative airports found their noise-dependent landing charge system, preferential runway system and movement restrictions on their own noise measurements. This proceeding enables a higher number of measurement points (in contrast to only three for ICAO certification), several noise metrics (e.g. continuous sound pressure levels, in contrast to single event metrics) and the consideration of the distribution of the surrounding population. The closer correlation to the actual environmental impact provides for a clearer dose-response relationship. Such noise levels are then determined by airport (runway use), airlines (fleet mix) and air traffic control (flight tracks). Aircraft design interferes with these aspects by influencing the respective peak levels, duration and frequency spectrum of a single event. However, current aircraft design has not yet fully incorporated research concerning the impact of noise, which has mostly influenced land use management, resettlement and compensation schemes.

Similarly to noise, the impact of pollutant gases is not yet directly considered in aircraft design, as neither air quality nor global warming are regulated in conjunction with aviation. At airports, however, the sustainable protection of occupational health will call for substantial reduction of NO_2 and HC (ozone precursors) as well as PM_{10} and SO_2 emissions. To limit global warming caused by aviation, still CO_2, but also NO_x and soot emissions have to be reduced and the formation of contrails hindered. Both local and global impacts require substantial advances in aircraft (e.g. drag and weight reduction) and engine design (e.g. low NO_x combustors or engine layouts for minimum contrail formation [42]). Besides, operations bear a high potential to further reduce emissions, both at airports and in cruise flight. New procedures could include single/reduced engine taxiing, low thrust take-offs, front wheel drives, fuel cells instead of APUs, lower design cruise altitudes and speeds, less fuel sensitivity to flight altitude and speed. Most of these operational approaches are strongly interlinked with the aircraft itself and should therefore be considered at preliminary aircraft design level.

5 Holistic Approach for Environmentally Friendly Aircraft Design

Based on the analysis of environmental impacts and regulations, we suggest a two-layer environmental evaluation process including a single operation (one flight) and a multiple event (airport or global traffic scenario). This enables integrating dose-response relationships into aircraft design, both for noise and for emissions.

5.1 Single Event Approach

The single event approach consists of a standardised mission profile between two generic airports. They represent the most important regulations (international hub type) which may be exchanged according to regional peculiarities.

On top of the three ICAO noise measurement points and the LTO cycle-based emission calculation, several additional noise calculation points beneath and sidewise the flight track and more operationally relevant metrics (e.g. SEL, L_{AMAX}) are used for noise evaluation. Furthermore, noise contours (e.g. 80dB L_{AMAX} area in km^2) are calculated to visualise the noise reduction potential of new concepts of aircraft and operations. This approach reflects more precisely the noise characteristics of an aircraft and enables a better distance-related estimation of its community impact (single operation dose-response relationship).

The evaluation of pollutant emissions is based on a refined LTO cycle, which, in contrast to the ICAO certification standard, allows for different operational conditions (e.g. variable thrust settings, 3° or 6° ILS glide slope). The impact on climate change is evaluated by an atmospheric metric that takes into account the altitude (cruise altitude) of the emissions (metrics currently developed by [43][44][45]). The linkage through operations (airport and cruise flight) enables an emission-related evaluation and optimisation of an aircraft, in contrast to the current emission certification, which considers the engine only.

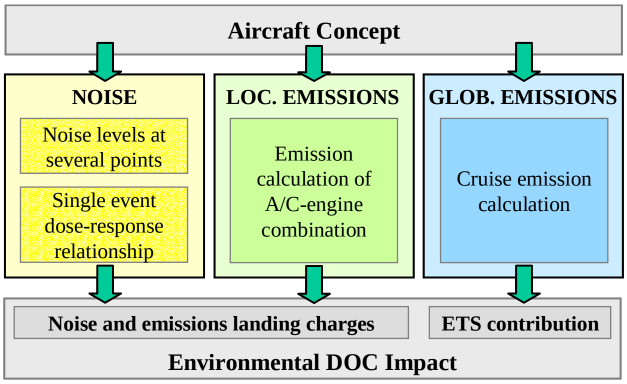

Fig. 3. Economic evaluation in single event approach

To combine the impact of noise and emissions in a single metric, the respective aircraft designs are evaluated as to their impact on environmental DOC, which depends on the respective regulative framework (Fig. 3). However, this approach presumes that noise- and emission-related charges reflect variable airport operations and that the aviation sector will be included in an emission trading scheme. Nevertheless, DOC represent a potentially appropriate metric to evaluate a single operation on noise, local and global emissions impact. As a first attempt of this approach, TUM has performed a noise and emission trade-off for different flight procedures [46].

5.2 Multiple Event Approach

Going beyond the single event approach, the full assessment of the environmental performance of an aircraft in terms of its real impact (see chapter 2) can be achieved by a multiple event approach.

A complete generic air traffic scenario is used. Noise and local emissions are evaluated respecting airport layout, fleet mix, population density and land-use information. Global emissions are evaluated for a global traffic scenario. This multiple event approach allows the determination of continuous sound pressure levels (e.g. L_{DEN} and L_{EQ} needed for annoyance and sleep disturbance), detailed emission concentrations around airports (by dispersion calculation) and a quantification of the radiative forcing (warming) of aviation. An aircraft designer can thus assess the **environmental footprint** of an aircraft concept (design, technology, operations) with a certain market penetration in comparison to a base scenario in an operational and therefore more realistic setting.

The following indicators define the overall environmental performance:

- Noise contour area and levels at defined points
- Inventory of emissions around the airport (emission carpet size of a fleet mix for one year of aircraft sources only) and for global traffic, both including a representative number of aircraft of the investigated type
- Percentage and total number of people affected by noise or emissions (with dose-response relationships describing health and annoyance), impacts on buildings/materials and crops
- Radiative forcing (temperature change) due to the operation of the investigated aircraft

Again, a common monetary unit enables the equal consideration of all environmental impacts. For the multiple events approach, external costs can reflect the effective environmental impact. Furthermore, they allow defining observation levels and thresholds for both noise and emissions.

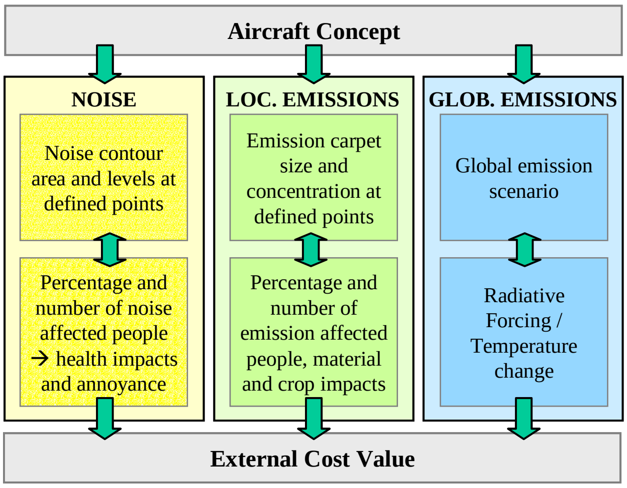

Fig. 4. Economic evaluation in multiple event approach

Compared with a base scenario in terms of total, aircraft specific and marginal costs, different aircraft designs and operational procedures can be evaluated, weighed and the most promising environmental concept can be carried out.

5.3 Drawbacks of the approach

Elaborating such holistic scenarios of airports (noise and local emissions) and global air traffic (global emissions) is very complex, comprises many sources of uncertainty and requires very detailed and comprehensive databases. To integrate such a methodology as a tool in preliminary aircraft design, a simplified model that is validated by intermediate control runs with the complex model, would be needed. The current methods for the calculation of gaseous emissions still are imprecise for thrust settings that differ significantly from the ICAO certification points. It is difficult to draw conclusions on airports that differ significantly from the generic airport. At last, the economic evaluation, especially of external costs, has some intrinsic shortcomings: statistic significance, data availability for dose-response relationships, derivation of values, acceptance, confidence level, different thresholds of noise and emissions.

Even if the application of the multiple events approach in aircraft design will require many further studies, a comprehensive single event approach as described in chapter 5.1 should be feasible right now.

6 Summary and outlook

One can assume that future regulations of aviation will represent the environmental impact better. Its early consideration in aircraft design will therefore be vital for the manufacturers.

Finally, producing an impact-related aircraft will be an economic asset for the aircraft manufacturer.

We hope to foster the discussion how aircraft design can contribute to minimise the environmental impact of aviation in order to assure a sustainable growth of the industry.

7 Abbreviations

A/C	Aircraft
AMS	Amsterdam airport
APU	Auxiliary Power Unit
ATC	Air Traffic Control
BImSchV	*Bundesimmissionsschutzverordnung*
CAEP	Committee on Aviation Environ. Protection
CDA	Continuous Descent Approach
CDG	Paris Charles de Gaulle airport
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOC	Direct Operating Cost
ECAC	European Civil Aviation Conference
EC, EU	European Community/Union
END	Environmental Noise Directive
EPNL	Effective Perceived Noise Level
ERLIG	Emission Related Landing Charges Investigation Group
ETS	Emission Trading Scheme
FAA	Federal Aviation Administration
FRA	Frankfurt airport
ICAO	International Civil Aviation Organization
ILS	Instrumented Landing System
IPCC	Intergovernmental Panel on Climate Change
HC	Hydrocarbons
L_{AMAX}	Maximum A-weighted sound pressure level
LASPORT	Lagrangian Dispersion Model for Airports
LBA	*Luftfahrtbundesamt*
L_{DN}	Day-night weighed continuous sound pressure level
L_{DEN}	Day-night-evening weighed continuous sound pressure level
L_{EQ}	Unweighed continuous sound pressure level
LHR	London Heathrow airport
LLT	*Lehrstuhl für Luftfahrttechnik*, Institute of Aeronautical Engineering
LTO	Landing and Take-off Cycle
MUC	Munich airport
NAAQS	National Ambient Air Quality Standards
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
OECD	Organisation for Economic Cooperation and Development
O_3	Ozone
$PM_{10}/PM_{2.5}$	Particulate Matter (< 10 / 2.5 µm)
PPM	Parts Per Million
RF	Radiative Forcing
RNAV	Area Navigation
SEL	Sound Exposure Level
SO_2	Sulphur Dioxide
TUM	*Technische Universität München*, Technical University o f Munich
WHO	World Health Organisation

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