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THE ENVIRONMENTAL CHALLENGE AS CHANCE FOR THE NEXT CENTURY AIRCRAFT DESIGN

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Abstract.

The general tendency currently strongly expressed in the aeronautical community is that the years to come are characterised by production cost saving and lead time reduction. Technological developments seem to have reached a certain saturation level and often financial analysts miss the cost benefits. However, the future challenges require further technology advancements, but technologies of a different quality.

One of the major challenges for air transport in the next century is certainly the environmental aspect. The present paper takes a fresh look on how these upcoming requirements can translate into a competitive chance for the next century aircraft design by looking into the achievements, future market and legislation requirements as well as design and operation of aircraft. Finally two different design approaches will be discussed presenting potential benefits from aircraft configuration and technologies for environmental criteria.

Introduction

The fuel crisis about two decades ago initiated a strong systematic effort to advance technologies. Today's driver for further technology development is seen in the environmental issue, the general question of adapting the growing number of operated aircraft into the air transport system and in the challenges arising from new categories and new configurations of aircraft in the next one or two decades.

While in the 70's the Club of Rome predicted that the limited energy resources will finally lead to the break-down of society, today, more than 20 years later a new simulation of the global system foresees that we will not even reach the end of our natural energy resources because long time before that environmental pollution will massively threatening our living conditions and reduce the basis for industrial growth.

Thus, it seems that all future scenarios for industrial development see as one of the current major challenges ahead the environment development. This is also the case for the air transport system where we now experience

- growing public concern stimulated by various reports in the media
- the market response by airlines, airports, etc.
- and last but not least political considerations and proposals for restrictions and possible taxes

With the advent of commercial aviation after World War I, the challenge of economic operation appeared. Improving design to reduce aircraft operating costs or increase its revenue potential, could only be taken after some experience had been gained in service and when effort and money was spent on a new product. This step was taken around 1930, and is now essential to all civil programmes.

Size, range and speed were the starting point of the basic design parameters of all transportation systems. Size has a proportional effect on the revenue potential of the product; range and to a lesser extent speed, shape the demand for the service.

Safety came very early as a design requirement, although the use of quantified probability analyses and safety levels is fairly recent. Safety is not a field for trade-off, certification requirements and quantified safety objectives must be met.

Operating economics appeared next on the requirement list. Improvement in operating

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economics of more than 70% (basis 1933) has been, and is still, achieved by aircraft size but size was in itself the result of technical/technological progress of both the airframe and engine manufacturers. The additional design parameter „environmental compatibility“ is focused primarily on external noise, emissions, production, maintenance procedures and eventually even the question of recycling. In the following a basis for discussion is provided by looking into the industrial developments in the future. These will largely depend on the requirements originating from the market and possibly legislation and thus, with emphasis on environmental aspects will determine the product and technology strategy.

The present balance of economical and ecological achievements

Over the past decades aviation has been contributing largely to industrial growth and globalisation. In order to judge the status and achievements with regard to the environmental question and to discuss the present balance of economical and ecological costs we have to consider the two main topics emission and noise separately. Other environmental issues like land-use cannot be discussed extensively. However, it should be noted that aviation uses less than 8% of the land required for rail transport and less than 1% of that required for roads. In terms of number of people moved, aviation uses this land five times more efficiently than rail and six times more efficiently than road.

Emissions

World air traffic experienced a growth of approximately 5% per year but at the same time due to the quest for improving operating economics fuel consumption was considerably reduced helping equally the environment. The fuel burn for various flight phases is shown in Fig. 1. For a typical long range flight of 4500 nm the emission distribution is presented in Fig. 2. Thus, CO_2 and H_2O emissions are only depending on aircraft fuel burn while the other emissions are additionally a function of engine combustion processes as well. Specifically the NOx production is shown over a typical flight mission.

Considering that the average flight efficiency can be expressed by

$$\frac{TripFuel}{Distance} \approx \frac{SpecificFuelConsumption}{Machnumber} \times \frac{Weight}{AeroEfficiency}$$

then using Airbus Industrie's products as a reference over the past twenty years the trip fuel has been reduced by about 37% and thus, the emissions have been decreased as well, see Fig. 3 [1].

This trend is not only an academic exercise but is supported by reports from airlines. Under operational procedures and with load factors of about 70% Lufthansa German Airlines publishes the average fuel burn of an A340-300 on long range routes to be 3,9 ltr./100 passenger kilometres while in charter operation at LTU the A330 only uses 2 ltr./100 pk. Since the mid-1970's airline energy efficiency has improved at an annual rate of 3-4%. As will be discussed later the future improvement potential is in the same order of magnitude.

Summarising the global impact of air transport on the environment the following statements represent the actual status [2]:

- aviation consumes just 5% of the annual world oil consumption and only about 12% of the oil supplies taken by the entire transport industry
- scientists estimate that jet aircraft produce about 2% of global man-made NOx emissions and about 2% of CO_2 produced by burning fossil fuels
- jet aircraft engine CO_2 emissions are thought to be responsible for only 1 % of the future global temperature rise caused by man made CO_2 emissions
- unburned hydrocarbons (HC) and carbon monoxide (CO) emissions by aircraft are of negligible importance.

Noise

Since the beginning of powered flight external noise was connected to the noise originating from the engine. The jet engine noise sources are mainly on the inlet side the compressor, the fan and on the exit side the turbine (combustion), the fan exit and the hot jet. The engine manufacturer have been able to reduce all the noise sources dramatically especially with introduction of higher by-pass ratio engines. The trend of the achieved noise reduction over the past decades is shown in Fig. 4 considering cumulative certification levels.

Apart from certification of the aircraft the manufacturer today's status is characterised by increasing operational restrictions due to noise regulation on airports. About 550 airports world-wide are exercising a number of restrictions like curfews, Noise Abatement Procedures (NAP), preferred runways, run-up of engines, quota counts, APU use, etc.. An increasing number of airports have installed microphone-sensors and judge the aircraft by their actual noise level. Landing fees often include noise-dependent contributions. In summary the actual noise situation is characterised by [3]:

- large and effective improvements over the past decades resulting in lower noise levels despite increased traffic. Example is Frankfurt airport in Germany where in 1995 the noise level was 26% lower than in 1980 while 56% more take-off and landings were taking place [4]
- world wide it is reported that the number of people directly affected by aircraft noise today represents just 5% of those affected in the 1970's.
- the intrusive footprint of noise created by modern aircraft like A320 covers only 1,5 square kilometres and lies within the airport boundaries at 85 dB(A).
- complaints about aircraft noise today mainly due to 'Stage 2' aircraft as „single events".
- although all modern aircraft fulfil noise certification limits better than required local airport regulations are exercised which can be much more stringent than legislation and often are based on actual noise levels
- for modern aircraft due to engine technology there are conditions when aerodynamic noise is of the same magnitude as engine noise levels.

Economical/Ecological Balance

Ecological compatibility of aircraft does not start nor end with the responsibility of the airframe and engine manufacturer but is embedded in a cycle with a number of players, Fig. 5. Five main parties are involved, apart from the two already mentioned, also Air Traffic Control (ATC) and airports, the administration and finally the operator is part of the complex relationship. However, the cycle is only completed with the fare paying passenger as part of the public formulating in the end the political will.

Considering the aeronautical system as it is today and the environmental aspects as we understand them we certainly can regard this as a balanced result. The costs in the aeronautical system with long development times, capital intensive investments and long product lives is well tuned with noise and emissions stringencies as well as production and operational aspects with regard to environmental legislation.

The future growth of industry and the requirements for more stringent environmental regulations need to be balanced in terms of costs and timing. Further improvements in fuel efficiency, emissions and noise can be expected as new technologies become available and the window of opportunity for product implementation is open. However, despite substantial research efforts technological limits might arise in some areas. Here further improvements require a combination of measures, procedures and the involvement of all concerned. In the end we all, industry, the public and governments have to decide on the acceptable balance between our concern for the environment and the needs for mobility by the air transport system.

Future scenario for market and legislation requirements

All forecasters expect a doubling of air transportation within the next 10-15 years, Fig. 6. Is this the „future scenario" we have to deal with? Does it mean that in the second decade of the next century we have twice as much aeroplanes, twice as much noise, twice as much emissions and pollution? This certainly is a scenario of very low probability. Firstly, even if we consider that air transportation is a steadily growing industry, the time frame in which a doubling will occur is not fixed.
Secondly, the doubling of air transportation in terms of passengers moved does not automatically mean an aircraft fleet twice as large as we see it today, see Fig. 7.
But there are some more factors which have to be considered for a future air transport scenario, e.g. the capacity of the air transport infrastructure. Will the airport world be in a position to cope with the expected large number of aircraft in operation in the future? The answer is: some airports will be able others not, but it will be hard to persuade passengers to go to London, Frankfurt or New York instead to travel to Glasgow, Munich or Denver, because there is enough capacity left.
Another factor which has to be observed for a future scenario (at least in some parts of the world) is the growing competition on developing ground transport system (e.g. high speed trains). But for the sake of environment it would be desirable if an economic competitive situation could be avoided and a constructive co-operation and ecological optimised total transport system in the respective local regions could be achieved.
For the industry the step to reach these demanding environmental goals was to enhance the importance of NOISE and EMISSION as design parameters parallel to the more traditional economic parameters.

Key buying factors

Airlines decision concerning the acquisition of aircraft is not only governed by economics but a number of other aspects are included. These „key buying factors" as shown in Fig. 8 consist of economics, commonality and added value factors, the latter containing the status of environmental compatibility of the aircraft. These market demands are translated into the appropriate aircraft design including required validated technologies. The aircraft selection process (which governs as well the aircraft definition process with the manufacturer) is then as sketched in Fig. 9. Quantifiable effects as environment or infrastructure play a major role but also the economically unquantifiable factors are more and more influential for selection of competing products.

Noise

The ICAO noise certification system has been in use for almost 30 years and the initial aircraft engine emission standards and recommended practices have been adopted in 1981, Fig. 10.
Since noise is of continuous concern world-wide we have to expect either more pressure from the market or more stringent regulations in the future. But hopefully new regulations will recognise that the present prescribed flight procedures for noise certification are not at all in line with normal day to day operations, i.e. it has to be found out if a reduction of noise standards in accordance with present certification procedures will really lead to a reduction of noise nuisance of the effected population. In this respect it is also questionable whether the sideline noise is of any general importance. There is only a very small number of airports which have runways quite near to these boundaries and populated areas right on the opposite side of their fences.
In summary there is agreement in industry that external noise will play in the future an even more important role in marketing and thus as a decision criteria for airline assessment of competing products.
Therefore the goal is

- for new products (≅ 2004) cumulative -15 dB
- for new products (≅ 2010) cumulative > -20 dB

The general vision is

- to separate noise certification and actual noise level in operation (noise abatement procedures, fees, etc.)
- to base future certification on noise footprints (see Fig. 11) and delete the irrelevant side-line measuring point. A typical footprint of 75 dBA within the airport boundaries seems acceptable when in neighbouring housing areas a level of 52 dBA within the houses is claimed to be not harmful to human health
- to consider the airport as an „industrial area“

Emissions

We have to expect also more stringent emission rules. But it must be kept in mind that only emissions up to an altitude of 3000 ft above the ground are considered, in the LTO cycle, therefore only the air quality in the vicinity of airports is affected by this ruling. A number of studies have shown that in the airport vicinity the portion of pollution caused by aeroplanes is rather small compared to the pollution caused by ground traffic and other energy consumers. In the future the legislators will be looking also at emissions above 3000 ft since politicians are under strong public pressure. An extremely stringent scenario results from employing the Swedish emission tax model (based on the LTO cycle) also during the cruise phase. The economical impact is given in Fig. 12 where the DOC development is presented for today's basis, for a reduction of 30% on the catalogue price and for additional fuel related taxes. This extremely unbalanced scenario has been discussed in order to underline that sufficient time is needed to gain further scientific knowledge on atmospheric chemistry, to improve the aircraft technology base and to harmonise this with possible political decisions. Up to now too little is known about the impact of aviation on atmosphere and climate. The presently available models of the atmosphere are not satisfying, so that it is difficult to define what the impact of aviation is or will be and how to design and operate aircraft accordingly. Thus also industry is required to explain our politicians to support ongoing research work, perhaps even in a more urgent manner. In the past Airbus Industrie has been involved in some of these research programmes, e.g. MOZAIC. The goal of this research program is to contribute to the evaluation of aircraft impact by improving the scientific basic knowledge through extensive measurements of ozone and water vapour in the atmosphere. Automatic measuring units have been installed aboard 5 in-service Airbus A340 aircraft generating experimental data with excellent global coverage in time and space. This Airbus Industry initiated program was carried out by a number of European Research Institutes and supported by the participating European airlines. The project was partially funded by the European Community [6].

Aircraft operations in the future

Careful treatment of the environment is not only a matter of technology but also how to translate these technical achievements into operational benefits. The aviation community (airlines, airports, industry and authorities) are looking for optimal flight procedures in order to minimise noise and air pollution by operational means, taking into account the capabilities of future 4 D navigation systems, advanced flight management systems, advanced communication (data link) systems and advanced air traffic management systems. It will and it must be a concerted action of all the different elements of the total air transport system. New harmonised project requirements have to be faced by all parties involved, e.g. late flap/slat setting during approach, gear down shortly before touch down, idle power approach, steeper approach angles, steep initial climb after take off, power setting for take-off in accordance to actual take-off weight and actual atmospheric conditions, minimum taxi times, avoidance of cues for departure clearance, unrestricted and fuel burn efficient climb, larger bandwidth of optimal cruising altitudes, unrestricted descent (preferable with idle power), shortest/great circle distances between point of departure and destination, („free flight" with an estimated fuel burn reduction of more than 6%), avoidance of holding patterns, just to name the major topics.

Emissions and fuel burn

As long as there are only limited answers of atmospheric scientists as a sound basis for environmental compatible engine and aircraft design there is only one way to go. The reduction of fuel burn (and the respective emissions) is industries primary answer utilising technologies which enable the operator to handle the above mentioned in-service aspect as well as technologies which are focused on the aircraft development.
Considering the next twenty years of continuous, focused and efficient research it is estimated that another 50% net reduction potential in fuel burn is achievable, Fig. 13. A large part is contributed by aerodynamics including topics like laminar flow or adaptive wing technology. Engine manufacturers not only working on SFC reduction but also on improved combustion processes in order to keep NOx emissions to a minimum. Furthermore, materials and structural technologies as well as improved systems contribute to weight reductions of the aircraft and engine. However, almost all of these technologies are only successful when considered on an interdisciplinary basis. The technologies employed coupled with other aircraft requirements lead to modified or even unconventional configurations which in itself present lower fuel burns as an example.
Bearing in mind the time to validate technologies, and to implement them in products the entire potential of 50% fuel burn reduction will not be seen before the year 2020 in aeronautical products. However, compared to today's aircraft the A340-500/600 and the A3XX will reduce as an example CO_2 emission per passenger kilometre by 4% and 32% respectively.

Future environmental progress in design and production

Successful environmental protection must begin in early design phases and is strongly connected with parallel running technology programs. With the „Go Ahead" of an aircraft program about 80% of the life cycle costs are fixed and the potential for reduction in fuel burn, external noise, operational capabilities, materials and processes in production employed are determined at even earlier phases.
Specific needs and requirements for environmental compatible production will not be discussed in detail. However, it has to be mentioned that in Europe various European Council Directives are implemented concerning environmental protection. At Daimler Benz Aerospace Airbus production processes have been optimised regarding reduction/ prevention of waste, air quality, water protection and noise. As an example over 70% of all waste products are presently recycled and the total process proves to be economical as well.
Apart from the well-known regulations for designing, producing and operating aircraft design offices today have to take the responsibility to implement environmental production goals as well. This starts already at the launching milestone for an aircraft study (a couple of years before go ahead). With the baseline configuration defined and the market opportunity identified environmental goals are fixed and they form part of the assessment criteria. Such a process „Design for Environment" is based on existing know-how, data and methods for improving and optimising the ecological and economical balance. New technologies certainly play a major role and their timing for validation must be in line with the aircraft program.
As one example of a specific part of the design process the development, production and implementation of a structural component of the horizontal tail shall be discussed. This horizontal tail support has been newly designed and compared to the existing part. The aim was to look at the total product- and life-cycle and assess the

energy used or saved respectively. Fig. 14 summarises the assumptions on the material, the production methods, the in-service utilisation and even the recycling process. While the existing part is made in metal out of the alternative materials CFRP (Carbon fibre reinforced plastic) was chosen. The resulting energy balance for production, for in-service life and for the recycling phase is given in Fig. 15 [5]. Not only is the CFRP support component to be produced with about 45% less energy but it saves during in-service 38 t of fuel over 20 years (at a weight difference of 12 kg). For recycling 70% less energy is necessary for the re-designed composite structure.
Next to the classical design parameters, „Design for Environment" will add another dimension. Apart from external noise, engine, emissions and infrastructural aspects the choices for materials, the production approach is undertaken to establish a record for the total energy consumed in construction and the energy saved over the entire life of this part of the aircraft.

Aircraft Design 2010

Based on the optimistic scenario that air traffic is growing like predicted, that technology programmes are successful and ready for implementation at market driven go-ahead milestones the following two examples of aircraft design are presented.

200 Seater

The design of a 200 seater aircraft for the next century depends strongly on the economic balance of cost of ownership and fuel cost at the entry into service date as shown in Fig. 12 for the basic DOC distribution . The cost of ownership represents about 30% of the DOC, the fuel cost vary between 20 and 30%. The assumed fuel price is about 80 $ gal. and the a/c price was already assumed to be 30% below catalogue level. The baseline aircraft in Fig. 16 shows a typical 200 seater configuration based on these economic assumptions.
Market forces or the protection of the environment concerning emission may cause increasing fuel prices clearly above the overall inflation rate and would then unbalance the DOC breakdown. A certain increase in cost of ownership would open a window of opportunity for the application of new technologies to reduce the fuel cost again. In the end tomorrow's economics may stay at a 30% balance between cost of ownership and fuel cost on a 4000 nm mission, but on a higher level of overall cost recovered by higher passenger fares, Fig. 17.
On the basis of Fig.13 one can extrapolate the potential fuel burn reduction over the next decades. However, only 50 to 60% of those potential improvements may be realised in the end due to restrictions in detailed design. The potential technologies have to be integrated in the aircraft configuration, which will lead to a rearrangement of the main aircraft components as shown in direct comparison to the baseline configuration in Fig. 16. This new generation aircraft is characterised by:

WING:
A large span „clean" CFRP wing without engines, slats and flap tracks and with natural laminar flow. A moderate sweep for a slightly reduced design speed. Reduced aerodynamic noise.
ENGINES:
Counter rotating shrouded propfan engines with an aft fan for optimum integration at the rear fuselage (clean wing !). Reduced engine noise.
TAILPLANE:
A laminar flow CFRP T-Tail for rear engine installation. Trim tank in horizontal tail. Reduced stability.
CANARD:
The weight concentration at the rear end of the fuselage moves the wing aft and the payload creates a forward CG position. A canard for this specific configuration could compensate the trim drag as long as the canard downwash could be separated from the wing and the engine intake.
NOISE:
Footprint of 75 dBA within airport boundaries.

EMISSIONS AND FUEL BURN:
30% reduction by aerodynamics, material-, structure- and engine technology.

Cryoplane

Compared with the more conventional design of a 200 seater as shown above the introduction of a cryogenic fuelled aircraft is more radical not so much from the point of view of engine/aircraft development but more considering the infrastructure. With regard to the Cryoplane the rationale is twofold, the careful treatment of our limited fossil resources and the protection of the environment.

Concerning kerosene or other mineral oil products it is estimated that at todays level of consumption the reserves are large enough to last a 100 more years. However, a cost increase above normal inflation certainly has to be taken into account in the long term whatever the reason. There will be a point in time when non-fossil, regenerative energy sources become of interest and economic as well. Cryogenic fuel appears to be a very attractive and acceptable alternative meeting environmental and technical requirements of aviation.

Cryoplane is the project name used by German and Russian companies working jointly on this subject since seven years. While the Russian interest centres around Liquid Natural Gas the German work concentrates on Liquid Hydrogen (LH_2). The benefits of LH_2 are summarised by production of the fuel utilising electrolysis of water (virtually anywhere in the world) and by the combustion products. The one and only primary combustion product of LH_2 is H_2O while the secondary emissions contain only NOx (compare Fig. 2 for kerosene). Due to several characteristics of hydrogen very low NOx emissions are achievable.

Comparing LH_2 and kerosene we find that the energy per mass relation is 1: 2,8 and the volume relation is 4:1. That means a relatively large volume for the tanks with very effective insulation is needed and this in turn requires configurational solutions to position these tanks compromising as little as possible the overall design. The higher energy content of hydrogen compared to kerosene can be utilised to the extent that despite additional weight due to tanks, insulation etc. an increasing payload benefit can be estimated increasing the longer the range. In Fig. 18 some tank positions are sketched and the potential payload gains are plotted. The status is that the feasibility has been shown by the Russian flight tests. However, there are a number of critical components which need technology development on the engine and airframe manufacturer side. In the medium term future certainly a demonstrator aircraft is needed to study the changeover of fuels, the operational effects, the public and political acceptance. Such a demonstrator could be in a first approach a small aircraft like the Dornier Do328. The long term goal certainly is to look at the Airbus family and the possibilities for a demonstrator for the medium- and long range aircraft sector, Fig. 19.

We cannot look into the future but we can prepare ourselves and with the presently envisaged scenario there is a good chance for market opportunities in the 21 first century.

Summary

One of the basic human needs is mobility. Coupled with the quest for industrial growth the aircraft industry plays a major role in today's world. Considering the aeronautical industry as a nation it would be placed number seven in economic power, a place currently held by Canada. The market demand for air travel and cargo is further growing at an annual average of 5% and 9%, respectively. However, environmental considerations become increasingly important for all areas of human activities (including agriculture).

Air transport certainly poses environmental questions when market demands develop as predicted but the industry takes the responsibility and prepares for the future. Environmental design, aircraft production, operation and in the end recycling are prime subjects where industry is working on and adequate technologies are being developed.

Manufacturers and operators have been successful in the past in minimising fuel burn , emissions and noise and it is strongly believed that they are able to continue this positive trend in order to keep the economic and ecological balance. The air transport system accepts the responsibility and takes up the environmental challenges regarding this as a chance for the next century aircraft design and operation.

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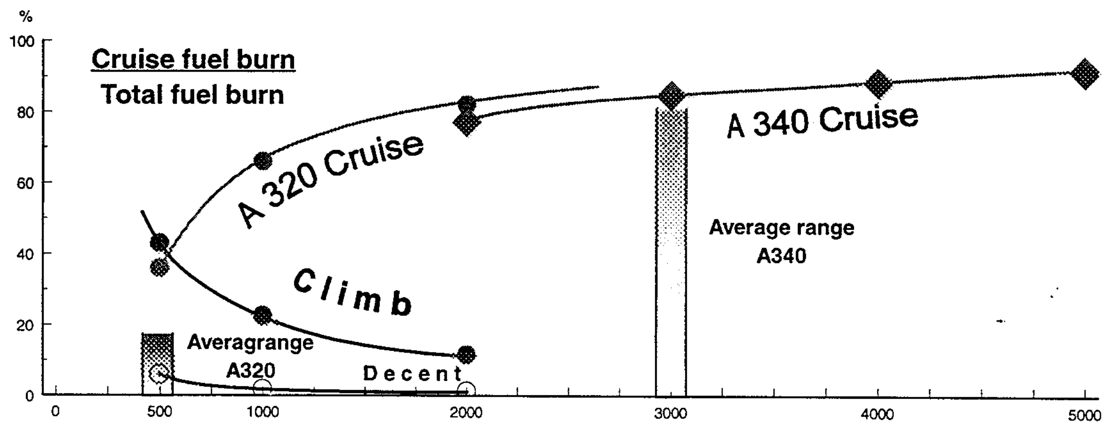


Fig. 1: Fuel Consumption vs Segment of flight profil Range (nm)

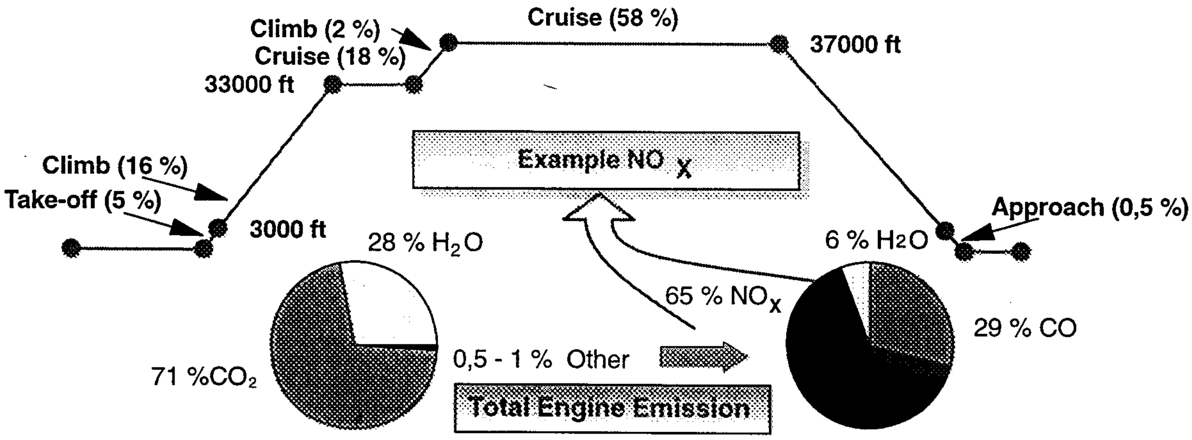


Fig 2: Engine emissions on long range flight

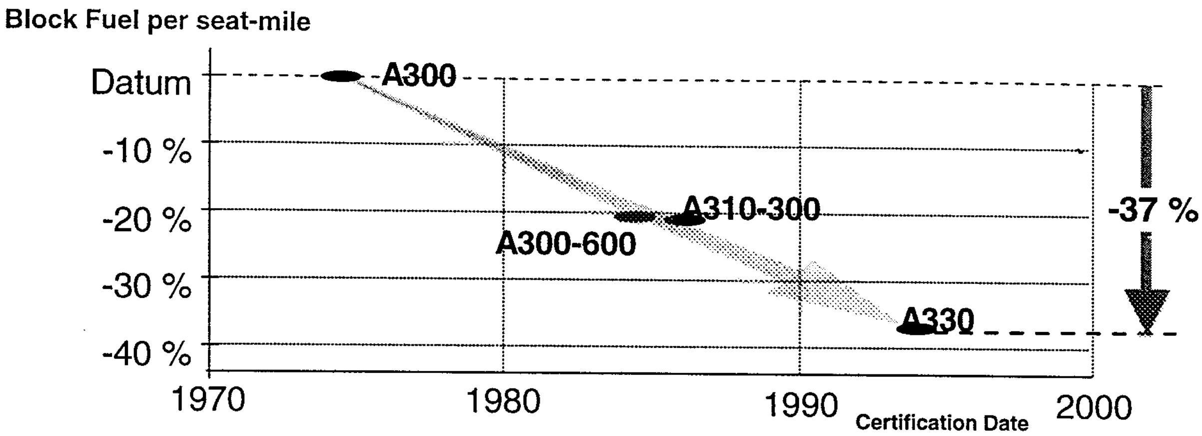
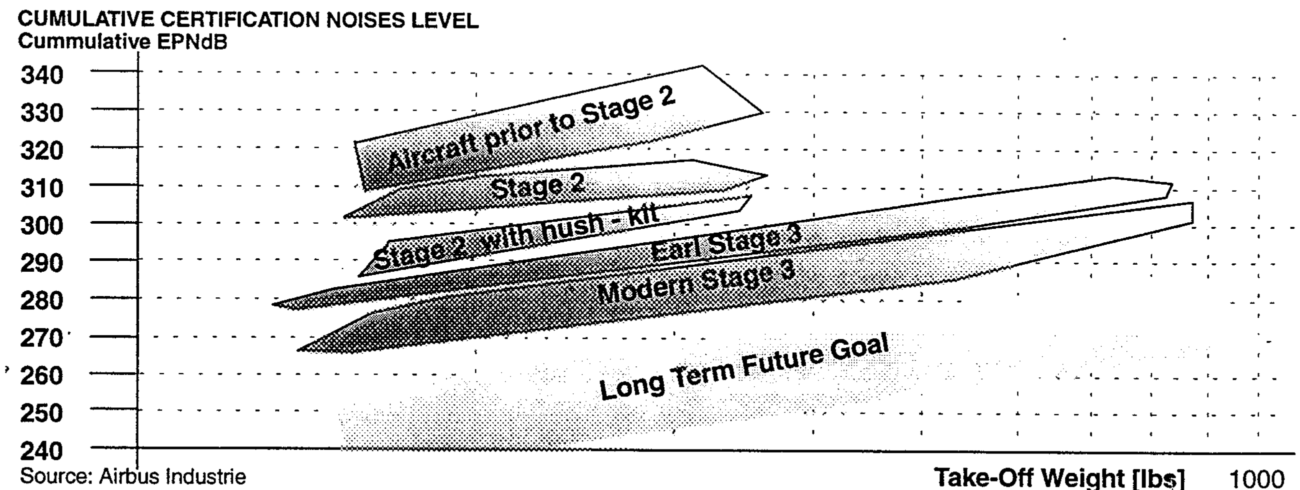


Fig 3: Impact of Technology



Source: Airbus Industrie

Fig. 4: Noise improvement since the beginning of the jet era

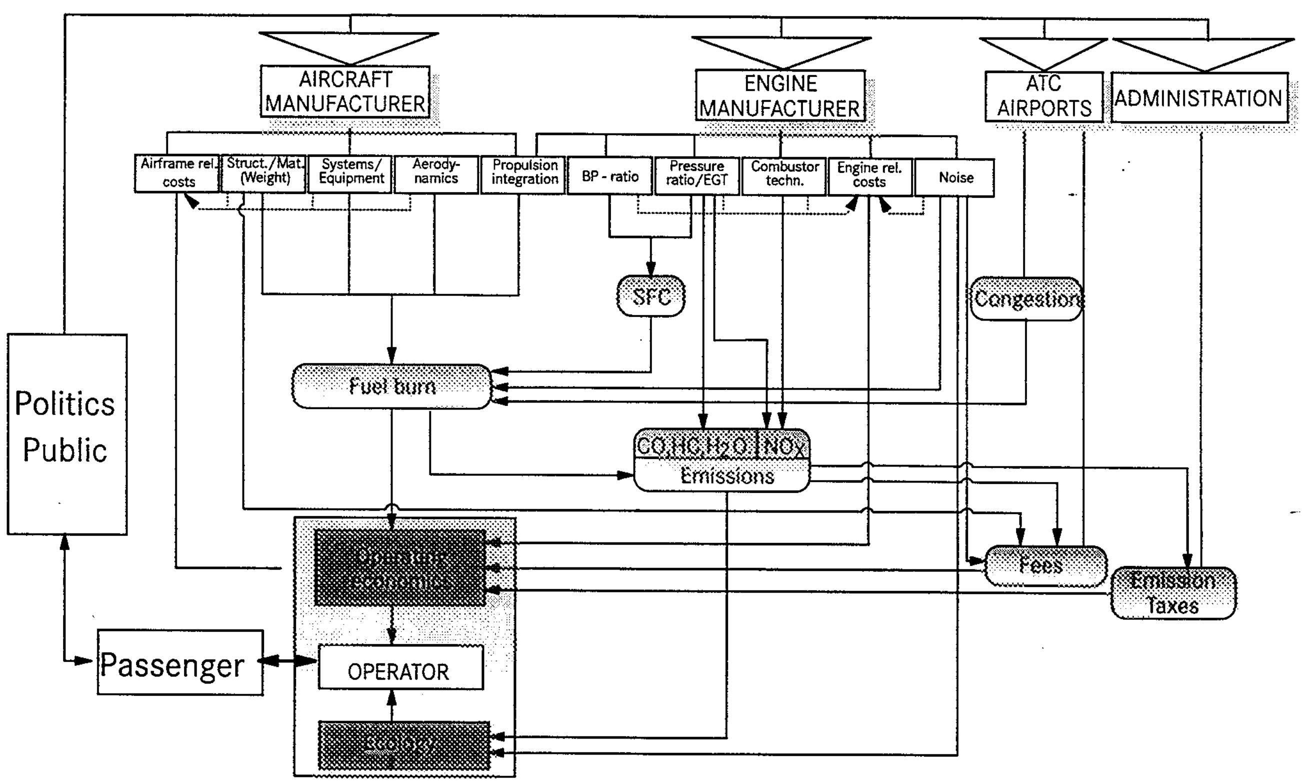


Fig.5: The ecological / economical relationship and responsibility cycle

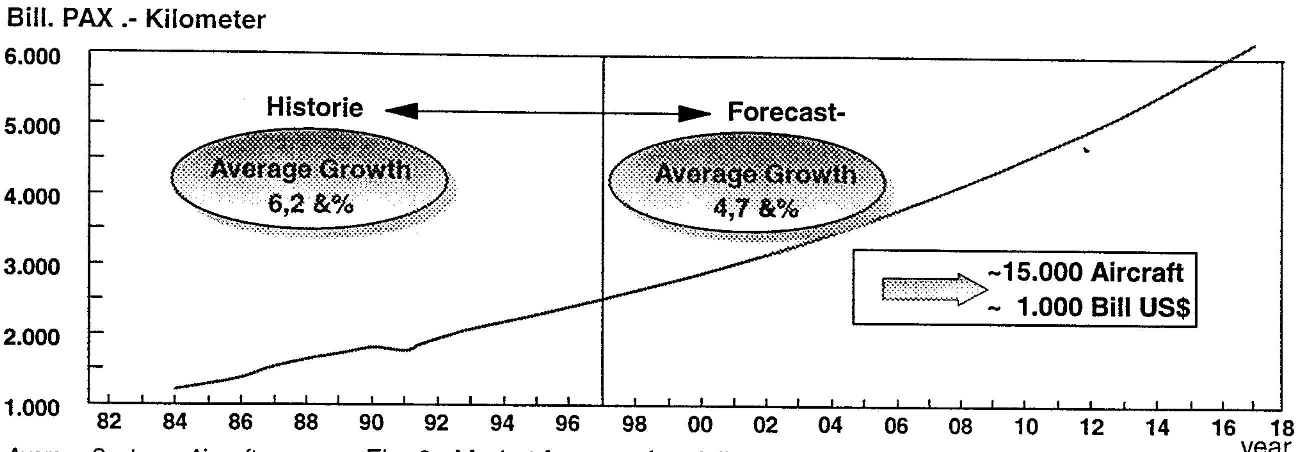


Fig. 6: Market forecast for civil transport aircraft

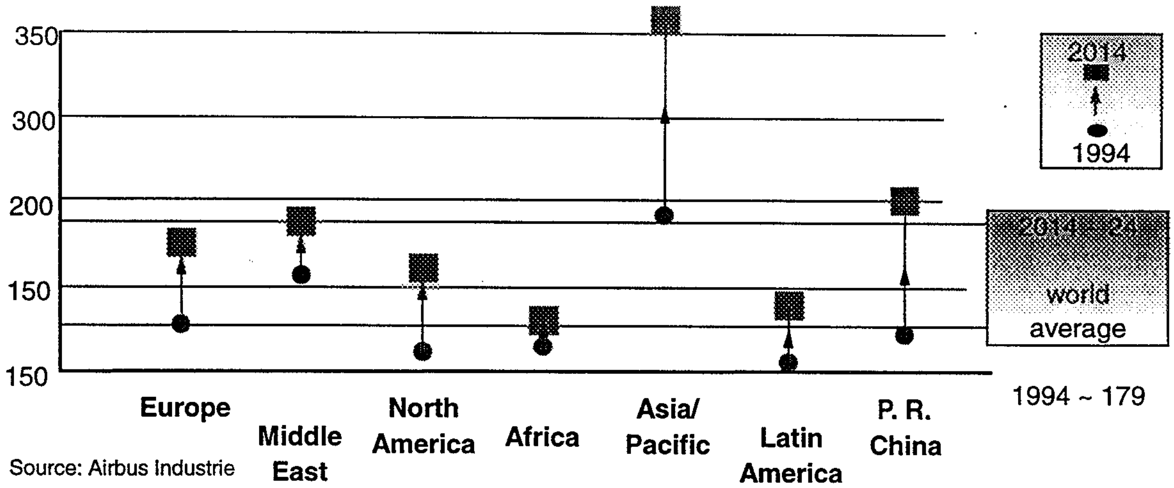


Fig. 7: Aircraft size growth over 20 years

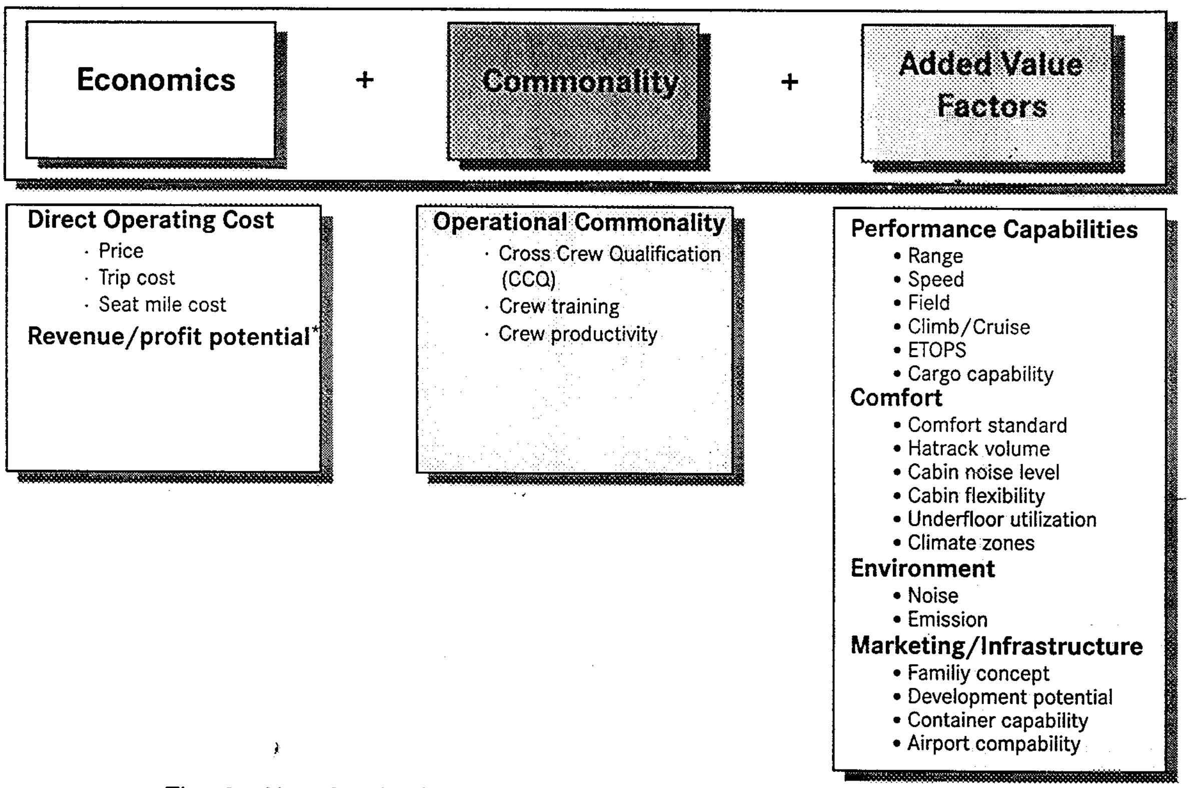


Fig. 8: Aircraft selection process as basis for product definition

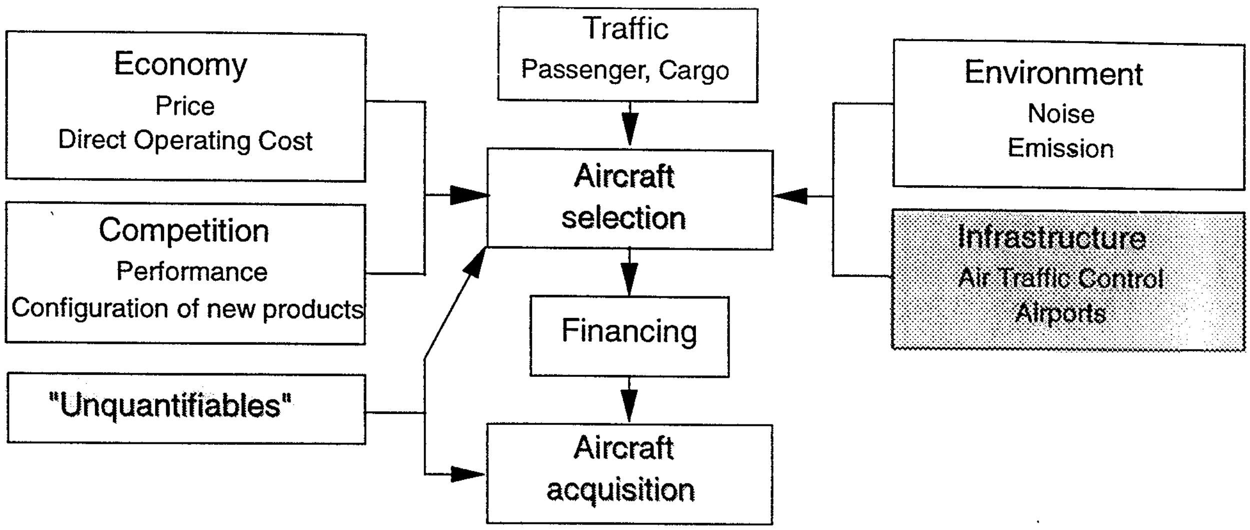


Fig. 9: Aircraft size growth over 20 years

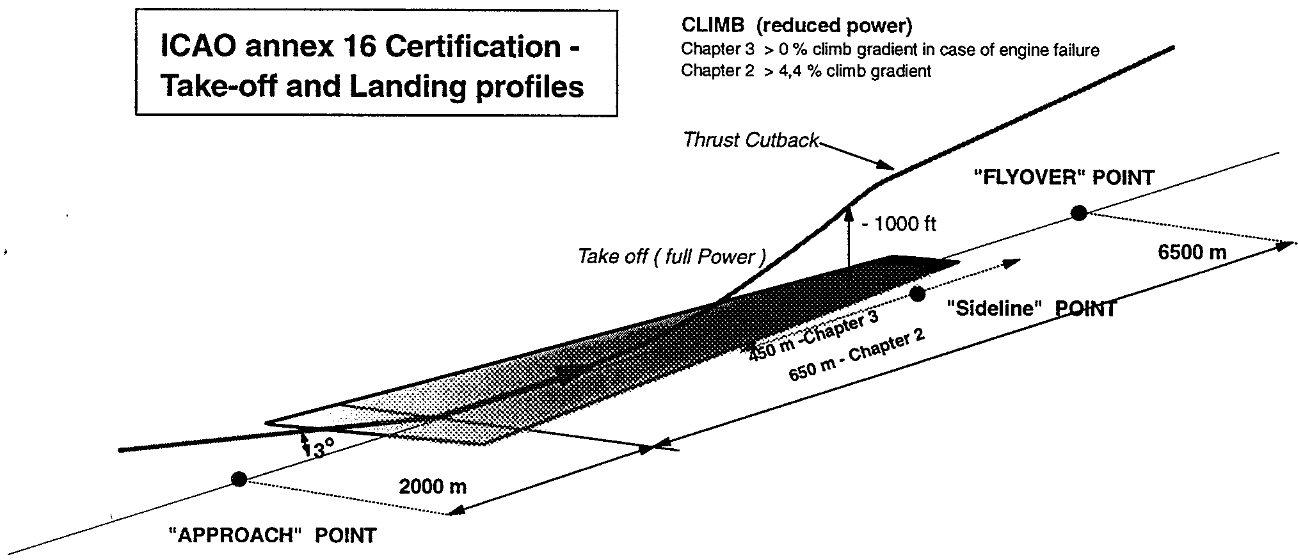


Fig. 10: Present noise certification procedure

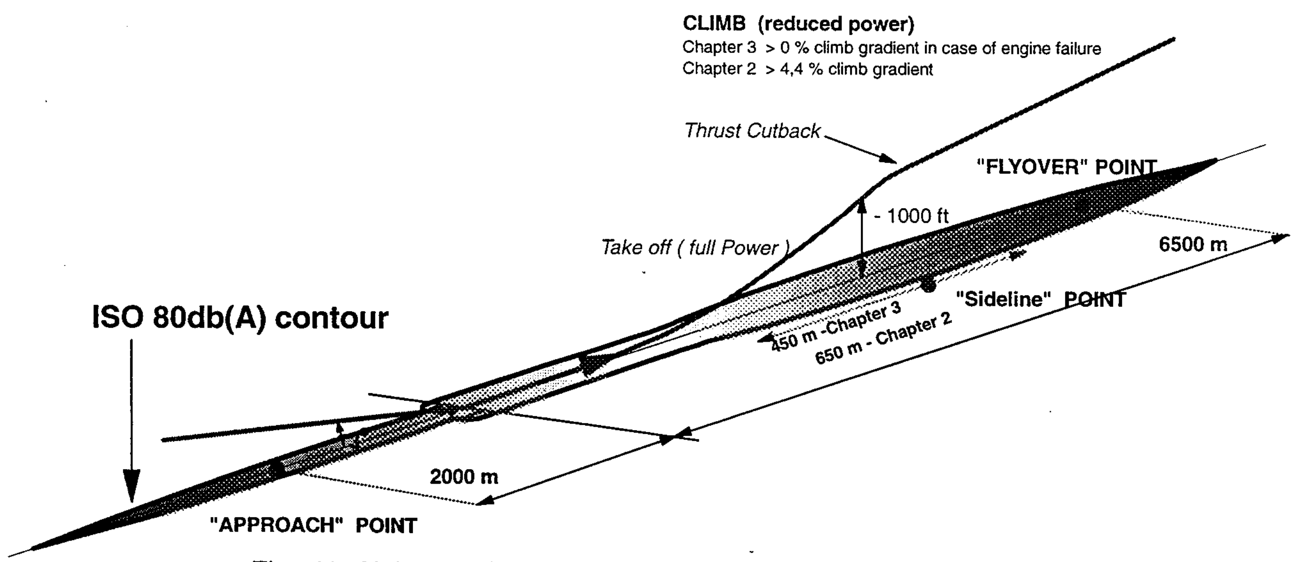


Fig. 11: Noise certification based on performance related footprints

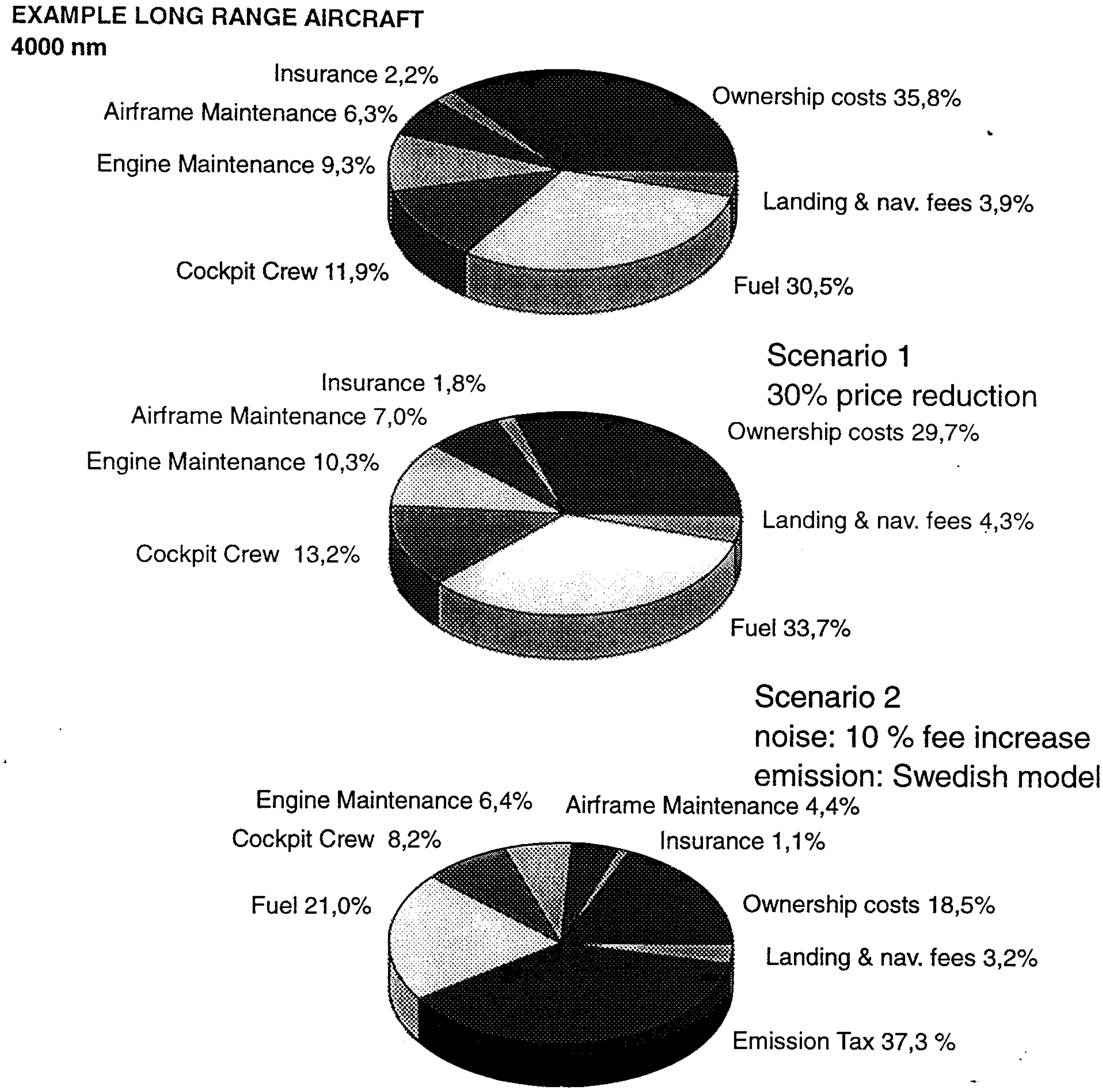


Fig. 12: Future Direct Operating Cost (DOC) Scenario

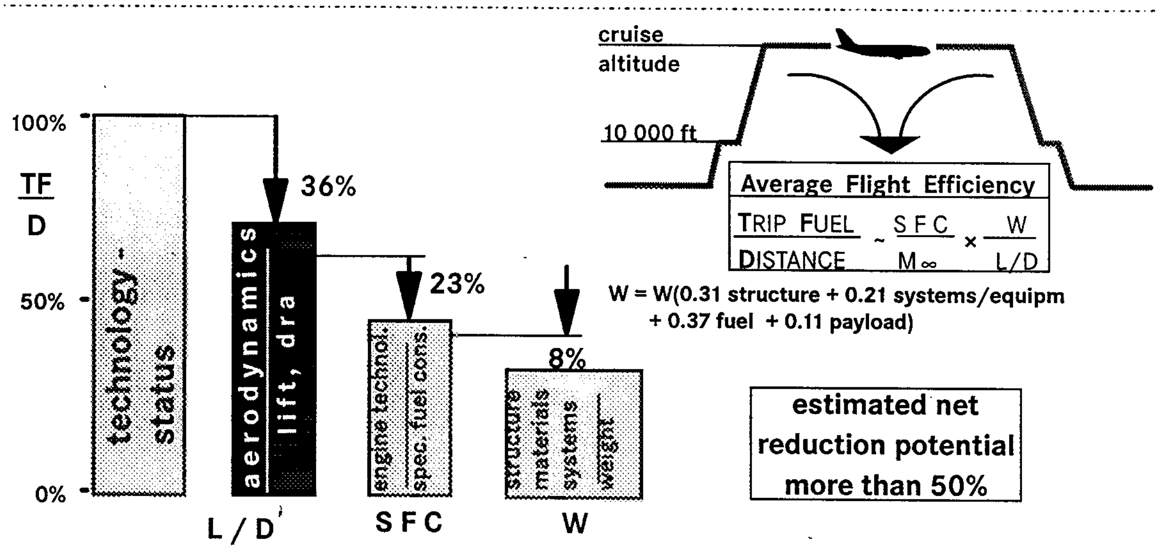


Fig. 13: Fuel reduction potential

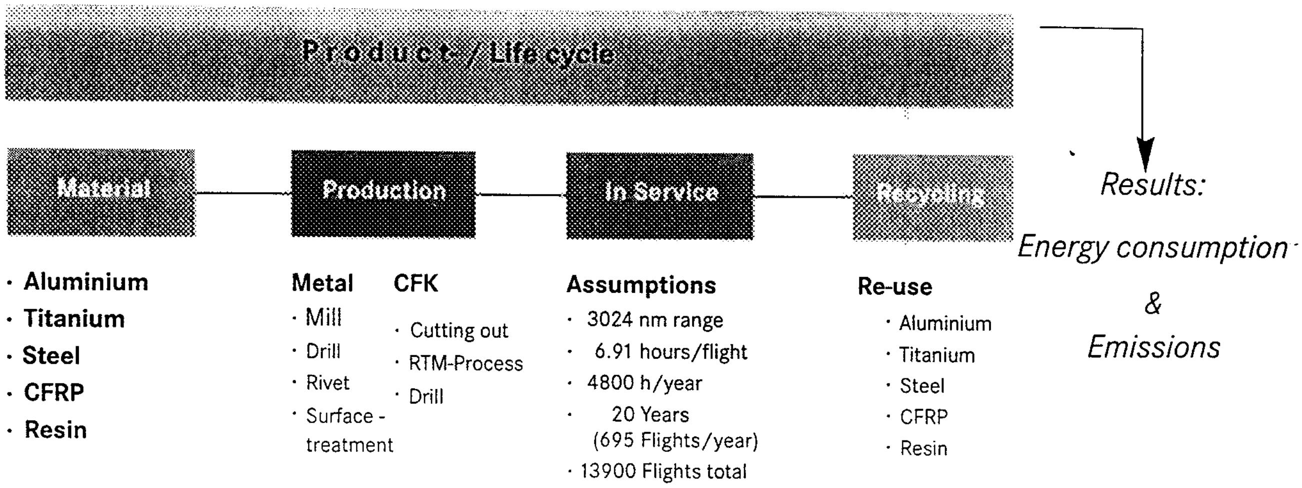


Fig. 14: Design for Environment - / Material Selection andAssessment

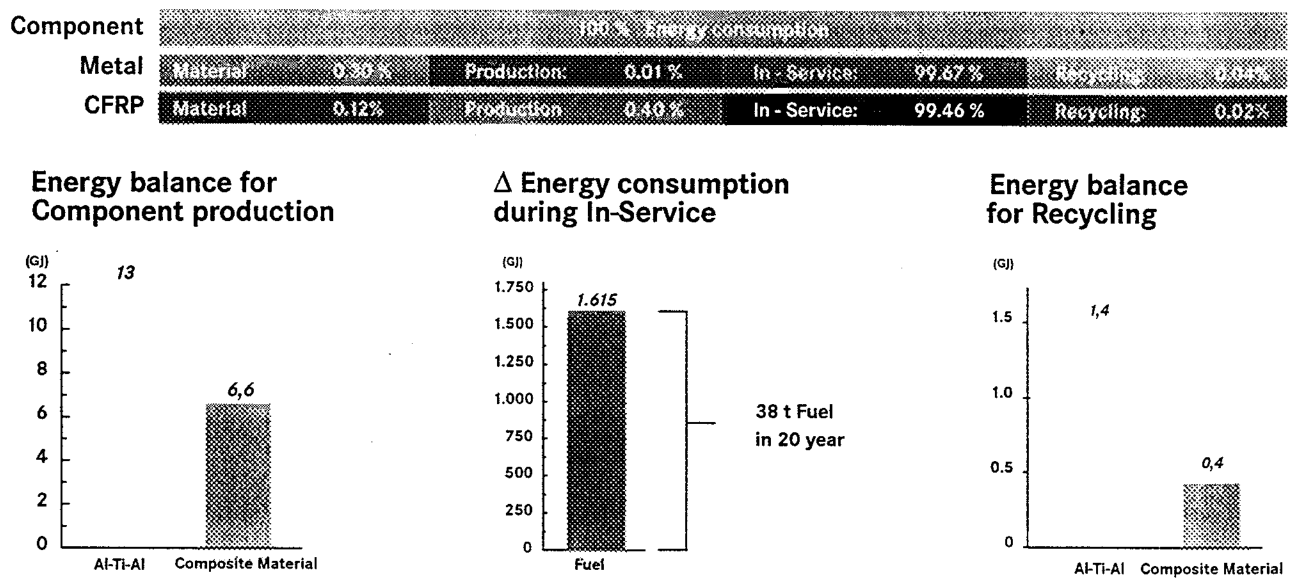


Fig. 15: Distribution of energy consumption for different components over life cycle.

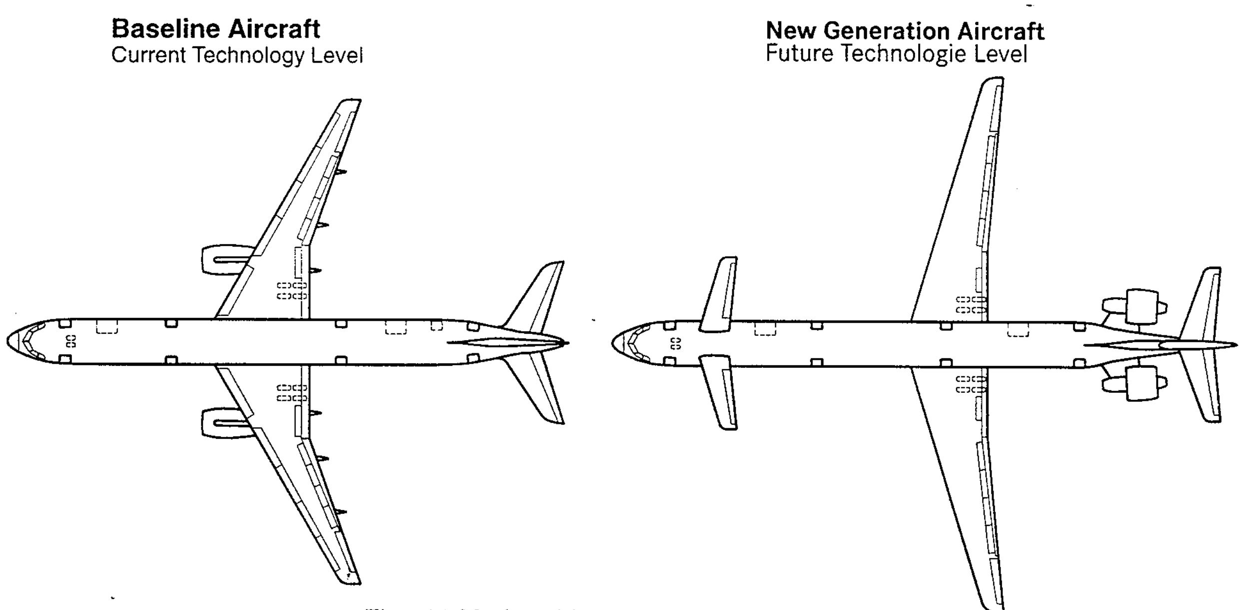


Fig. 16 Market driven configuration changes

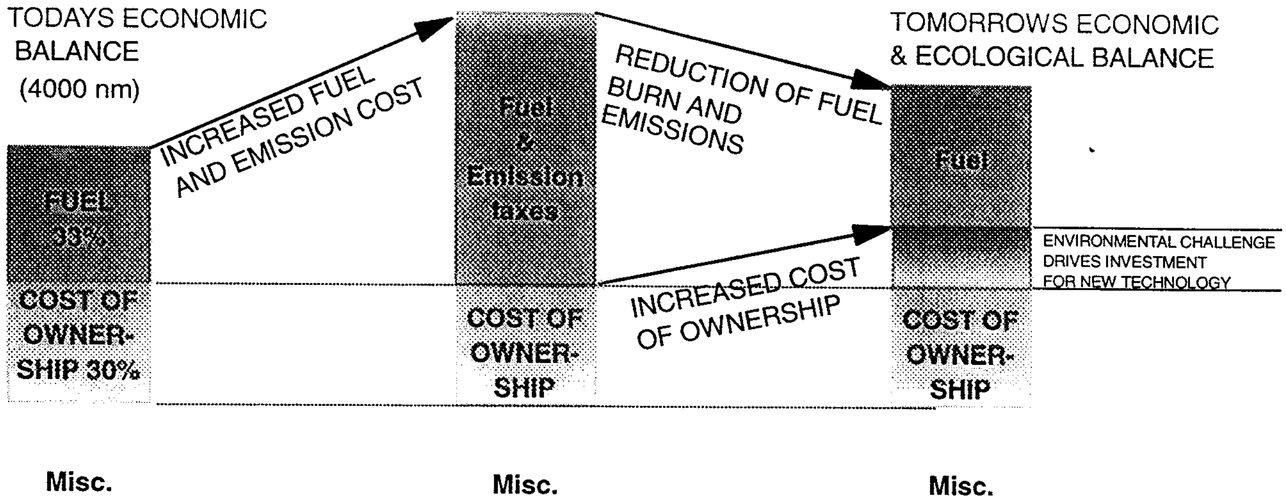


Fig. 17: Todays and future economic balance

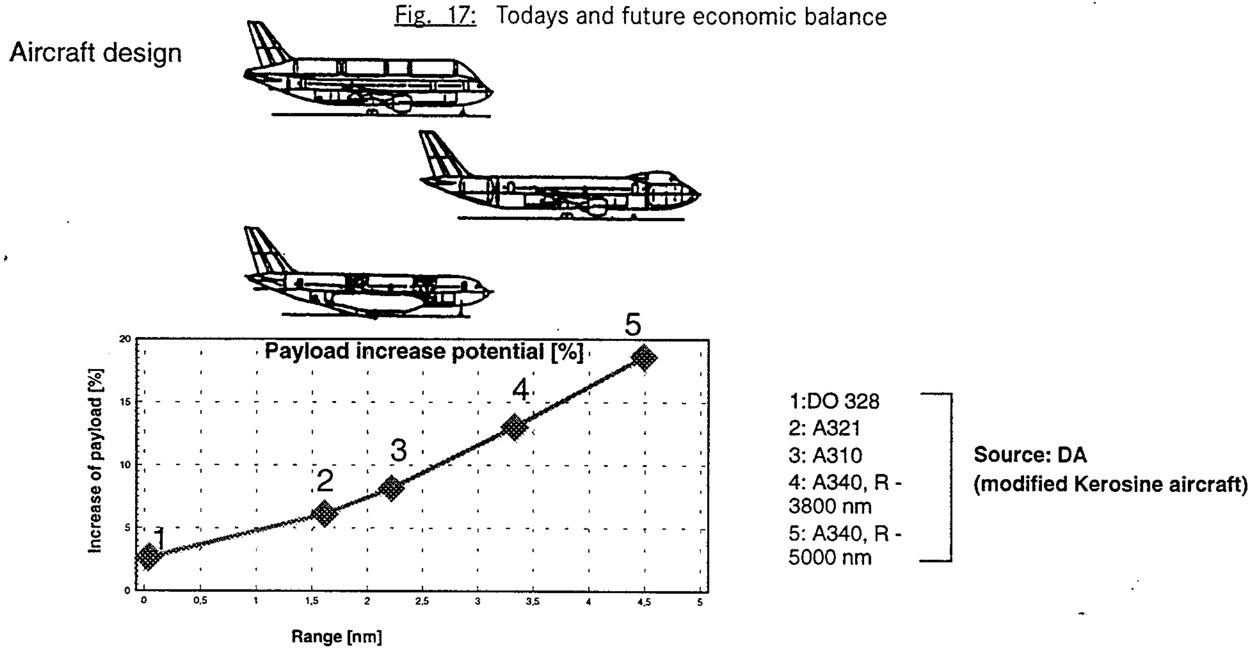


Fig. 18 Cryogenic aircraft configuration and payload benefit

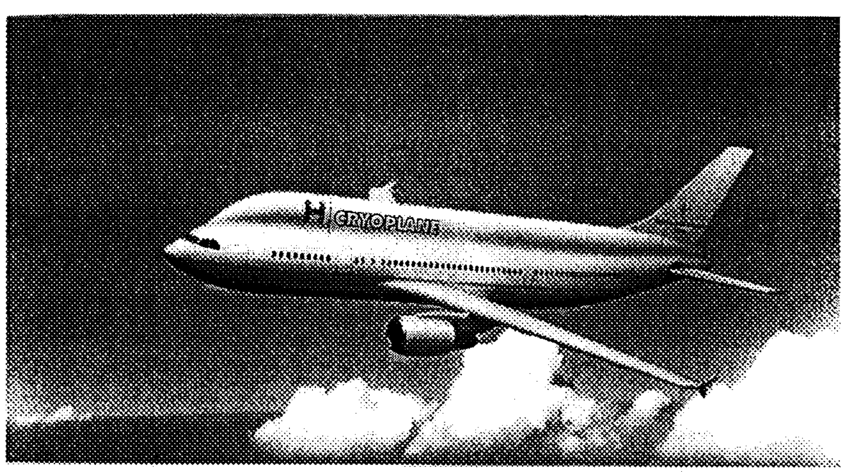


Fig. 19 Airbus cryogenic demonstrator