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IMPACT OF OPERATIONAL AND ENVIRONMENTAL ASPECTS ON COMMERCIAL AIRCRAFT DESIGN

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Abstract

Besides low operating costs design objectives such as operational flexibility and reduced impact of the aircraft emissions on the atmosphere recently play an increasingly important role in configurational aircraft development. Since both aspects affect the aircraft configuration it becomes necessary to take them as early as possible into account, e.g. in the conceptual phase, the first part of the configuration development. Therefore, the design-system CAPDA is extended with respect to a synthesis-implicit optimisation of the flight profile on the basis of typical utilisation profiles. This leads to optimum designs in terms of payload/range capability and operational flexibility. Examples presented show a significant impact of the aircraft utilisation pattern on the configuration layout. Furthermore, as a first approach to consider environmental aspects a modified merit function is introduced into the optimisation process extending the conventional DOC-breakdown by additional fees depending on altitude. In order to prepare environment-oriented flight routing and flight profiles configurational development depending on altitude and speed is discussed.

1 Introduction

The routes airlines serve are largely determined by the interaction of geographical, political, economic and social factors which are outside the airlines' control. The geographical location of the airline's home base together with the level of business and tourism interaction between the home country and other countries influence the sector lengths and traffic densities that can be lucratively operated. Here, the regulation of air traffic by means of bilateral and international air services agreements plays an important role.

These effects on airlines' operating patterns and passenger demand are reflected in the aircraft types which the airline operates and their utilisation. As an example, figure 1 compares the utilisation of the Boeing 747 of Singapore Airlines, Air France and Lufthansa German Airlines. The graph which bases on the evaluation of timetables emphasizes the influence of different home bases on the utilisation of an long-haul airliner with a design range exceeding 5000 nautical miles. The two European airlines operate this aircraft mainly on transatlantic routes to North America and on stages of less than 1000 nm collecting passengers for the long-haul flights. On routes between, say, 1000 nm and 3000 nm this aircraft is comparatively little used due to a lack of potential destinations. In the case of Singapore Airlines the situation is totally different because its geographical location results in a much more uniform route structure with a shorter average sector length. For the airlines shown most of the flights are performed for stage distances below the B747's design range. This consequently leads to a direct operating cost penalty.

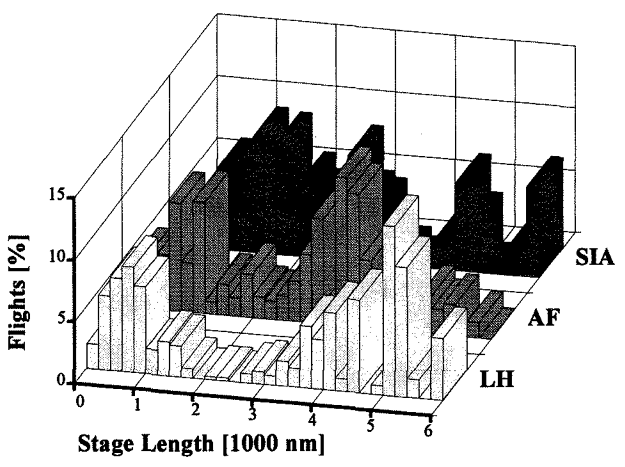

Fig. 1 Utilisation Profiles. Boeing 747-200/300.

As well-known the stage length is of fundamental importance for an aircraft's direct operating costs per seat-kilometre. There are a couple of factors which help to understand this cost-range relationship:

- Ground manoeuvre time and the relatively slow climb and descent phases of a flight become a decreasing proportion of the total block time as stage length increases. Consequently average **block speed** and hourly productivity rise. On the other hand, the direct operating costs per seat-kilometre fall.

- During taxying, take-off run, climb and approach fuel consumption is higher than in horizontal cruise. Its proportion of total fuel burn decreases with stage length. Hence, **block fuel** does not increase in proportion to distance and fuel costs per kilometre drop.

- Daily aircraft and crew **utilisation** depend on stage length. The more an aircraft flies, the lower become its costs. Higher aircraft utilisation and accordingly lower hourly costs can be achieved by longer stage lengths.

- On short sectors **landing fees and airport charges** are caused more frequently than on longer stages. Their impact on costs declines with rising stage length.

- Some maintenance checks are related to the number of take-offs and landings. Since these occur less frequently as stage length increases the **maintenance costs** are in inverse ratio to stage length.

All these factors show the same influence on seat-kilometre costs: They fall rapidly as stage length increases. For constant payload then they gradually flatten out until the longest possible range for the given payload is reached. For distances beyond this, they rise sharply as payload has to be sacrificed to fly further and productivity begins to drop(1).

Low direct operating costs over a wide range of sector lengths are equivalent to a great operational flexibility of a commercial airliner. The consideration of airline-dependent utilisation patterns during the aircraft design process promises to improve this operational flexibility. Taking into account this and the aspects discussed above it is desirable to substitute the conventional design point which is defined by a single characteristic flight mission (Mach number, payload/range requirement, cruising altitude and FAR-balanced field length) for a realistic utilisation pattern.

Besides operational flexibility future aircraft configurations may also be influenced by modified flight routes and flight profiles as a measure to reduce the impact of pollutant emissions on the atmosphere. In the last decades the development of new commercial aircraft was mainly characterized by integration of new technologies, such as transonic wings or new engines, which led to a significant reduction in operating costs. Especially the introduction of high-bypass engines resulted in a reduction of noise and fuel consumption. However, the total amount of air-traffic emissions increased continuously due to the increase of the world air traffic. Latest research results show that these emissions have a significant damaging effect on the atmosphere and - in case of subsonic air traffic - on the greenhouse effect.

Schumann(2) gives a comprehensive overview on possible effects of aircraft emissions on the atmosphere. Main variable of influence to the degree of damage is the altitude in which the emission happens. Emissions in altitudes below the tropopause have a minor effect to the atmosphere because of tropospheric cleaning processes (wind, condensation, rain). This leads to comparatively short times (days up to several weeks) for the emissions to stay in the troposphere. In contrast, above the tropopause missing vertical temperature gradients lead to an accumulation of emissions in the altitude they have been emitted so that concentrations of some 100% higher than the background concentration of these gases occur, figure 2.

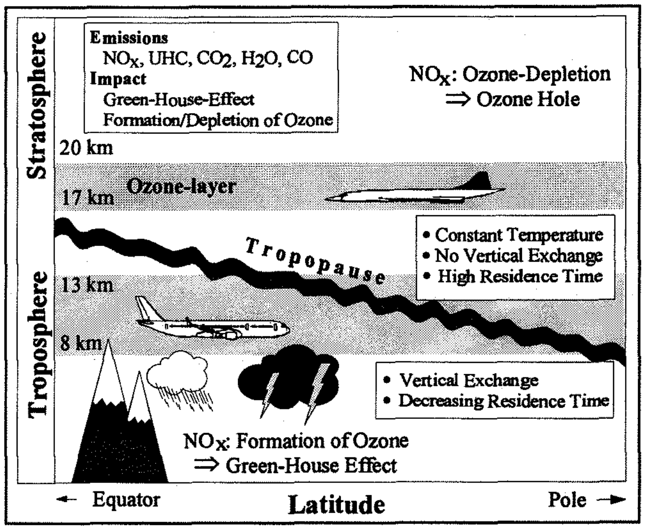

Fig. 2 Sketch of Environmental Scenario.

Especially the nitro-oxygens play a significant role in the production of ozone in the high troposphere and the low stratosphere(3). The additional ozone acts in these altitudes like carbon-dioxide and water vapour as a greenhouse gas. Beyond this the water vapour results in the formation of ice-clouds which reflect solar light and consequently influence the energy balance of the earth. Thus, the operation of aircraft powered with liquid-hydrogen with much higher water-vapour emission in altitudes above the tropopause needs further investigation. The amount of emissions(4) can be influenced by optimizing the aircraft geometry with respect to minimum fuel burn. This effect can be enlarged by treating airspeed as an optimisation variable.

Due to atmospheric cleaning processes lower cruising altitudes offer a potential to reduce the impact of emissions in spite of a higher fuel burn. Since the altitude of the tropopause varies with latitude modified flight routings represent further potential to reduce the impact of emissions on the atmosphere. Therefore it becomes necessary to simultaneously consider all geometrical and operational aircraft design variables which have influence on fuel consumption, the amount of emissions and their impact on the atmosphere, already during the conceptual design phase.

Since at this time no design systems suitable for the solution of this task are known, an extension of the CADPA-system for the conceptual design of commercial aircraft is expected to offer an adequate basis for these investigations. The integration of operational variables as well as environmental aspects into the design process requires a modification of the design-synthesis while the inclusion of the impact of pollutants in the optimisation process demands modified merit functions or multi-objective optimisation techniques.

The discussion of the operational and environmental design problems described above are the objective of this paper. All calculations have been accomplished through the design system CAPDA which allows the computer internal representation of aircraft geometry, performance as well as multivariate configuration optimisation with respect to various merit functions.

2 The Design System CAPDA

2.1 General

The design system CAPDA(5,6) allows the evaluation of various competing aircraft configurations and assists the design engineer in deciding which solution is worthwhile to be more detailed analysed in the following design phases. The design engineer operates the design system via a central user-interface. Doing this he is guided through the entire design process on the basis of an extensive information and documentation system, figure 3.

Starting with the mission specification the initialisation-module performs an approximation of the aircraft geometry on the basis of an extensive regression-analysis of selected aircraft stored in the statistical data base (SDB). This initial baseline design can be interactively modified due to the requirements of the aircraft to be designed. During the design synthesis the configuration is cyclic-iteratively analysed using a set of analysis methods selected from the methods library (ML). The consolidation process is complete, when all demands and design specifications are satisfied. The program system allows the optimisation of the consolidated baseline design due to different merit functions (DOC, MTOW, MEW,...) with several optimisation strategies leading to an optimized baseline design. Detailed analysis of flight mechanics allows the layout of the empennage. A step back to the initialisation module for interactive configuration changes is possible at any time. All results are stored in the project data base (PDB).

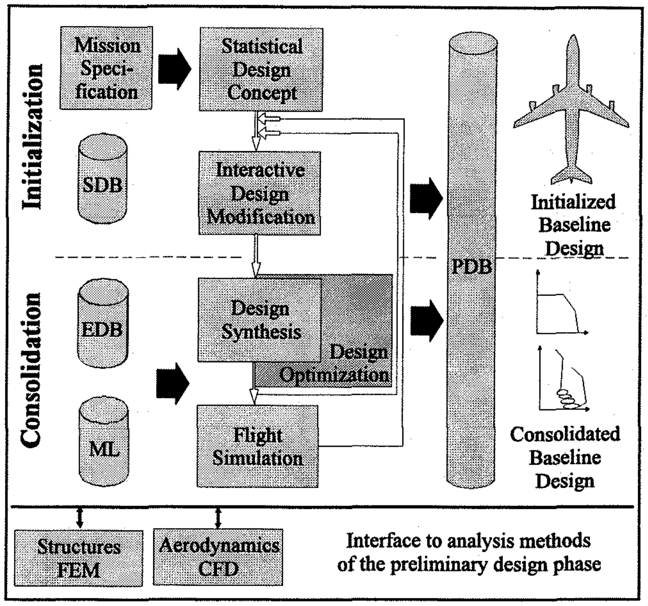

Fig. 3 CAPDA. Flow Chart.

2.2 Design Optimisation

Although generally every strategy for multivariate and restricted applications will be suited in aircraft design optimisation, three strategies have been implemented in the program system CADPA. The selection of the one or the other method depends mainly on the task to be performed and the experience the user has with the methods.

The most conventional approach is the tangent-search algorithm which is basically a modified Hooke & Jeeves strategy. This strategy is quite reliable but needs fully consolidated designs to modify the vector of design variables and shows - especially near an optimum - slow convergence leading to a high computational effort. For a better performance an optimisation technique has been developed, which modifies the design variables already during the design synthesis and shows a significant potential of time-savings for typical applications(7).

Including cruising speed and altitude in the optimisation, due to a poor convergence behaviour of the design synthesis this strategy will no longer lead to satisfying results. Therefore a third optimisation strategy has been developed and implemented into the program system showing the same computational performance of the synthesis integrated optimisation combined with the reliability of the tangent-search algorithm. This strategy allows the simultaneous optimisation of operational and geometrical design variables and is used for the application examples discussed in chapter 4.

2.3 Typical Applications

The main objective of the conceptual design phase is the parametric variation of as many design variables as possible to obtain the most promising concept with respect to a merit function. In the following two typical examples for the application of CAPDA are presented.

Since the development of a very large commercial transport aircraft is at present thoroughly discussed by manufacturers and airlines the first example treats the modelling of the fuselage geometry and the cabin layout of a 600+ seater. The accommodation of this large number of passengers cannot economically be handled by conventional fuselages and requires new fuselage concepts.

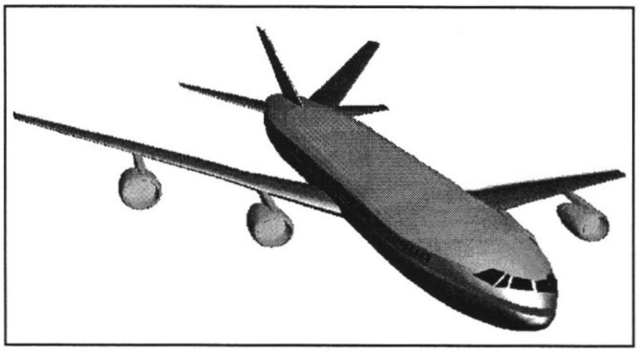

Fig. 4 600 Seater. Design of Fuselage Geometry.

The geometry model of CAPDA allows through graphical interaction the convenient creation of fuselage cross-sections which are composed of up to three ellipses. This is the basis for the design of several passenger decks and the detailed discussion of all associated questions, e.g. the optimum cross section with regard to the utilisation of fuselage volume and cargo capacity or the best ratio of fuselage diameter to length considering operational, aerodynamic and structural aspects. Ground handling problems due to external dimensions during passenger boarding and cargo charging or the evacuation of the aircraft in case of an emergency can be investigated as well as the optimal positioning of the cockpit or the shaping of the fuselage's nose and tail cones.

At the same time seating arrangements, position, number and size of galleys and toilets can be studied and in an iterative manner adapted to the fuselage dimensions. Finally, with the iterative interactive modelling of fuselage and cabin geometry as well as its aerodynamic and structural analysis the design engineer is provided with the possibility of creating the appropriate fuselage and cabin layout for a given design task. Figure 4 shows a shaded model of a wide-bodied fuselage for 600 passengers.

With the development of reliable and powerful high bypass engines it has become possible to operate safely and economically twin-engined long haul airliners. Among aircraft manufacturers and airlines the merits of the twin compared with the quad are controversially discussed. The central question is whether the quad's higher acquisition and maintenance related costs can be compensated beyond a certain stage length by its lower flying costs due to a more balanced design.

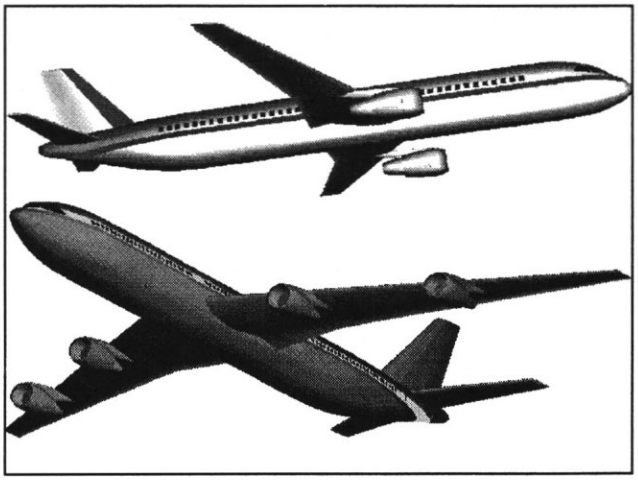

Fig. 5 Long Haul Airliners. Twin and Quad.

In order to investigate this matter a two- and a four-engined baseline design have been initialised with the design system CAPDA, figure 5. To get comparative results the fuselage geometry of both variants has been chosen identical while wing and empennage layout vary according to the different number of engines.

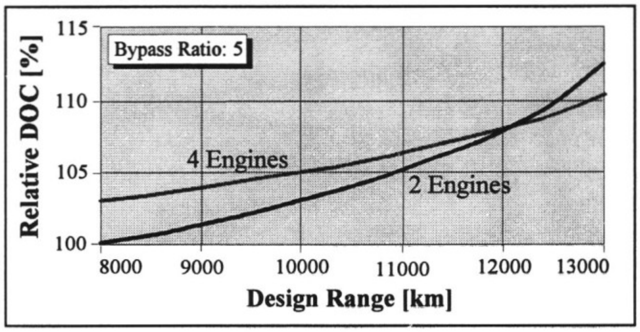

Fig. 6 Twin vs. Quad. Direct Operating Costs.

Figure 6 shows an evident influence of the design range on the direct operating costs of the consolidated baseline designs which however is different for the twin and quad configuration. Basically this results from their distinct shares of acquisition, maintenance and fuel costs of the total costs. In the given example the higher efficiency of the more balanced quad leads to a cost advantage for stage lengths beyond 12000 km. But the calculations have also shown that the intersection of both curves heavily depends on engine characteristics and bypass-ratio as well as on operational parameters, e.g. take-off field length or initial cruise altitude.

The two examples show that the CAPDA-system is particularly suited to effectively support the design engineer to obtain the most promising concept.

3 Configuration Development Considering Airline-Dependent Utilisation

3.1 Basic Idea

In classical aircraft design the configuration is developed with respect to a single flight mission which is generally represented through the design point. In principle the initial baseline design is repeatedly analysed in all design disciplines and, therewith, in an iterative manner matched to the design requirements. Hereby, the design range is regarded as a deterministic parameter which governs the configuration development. In order to take the complete operating pattern of an airline into account it becomes necessary to reconsider this approach because the design range in its classical meaning does not exist any longer(8). This leads to the following conclusions:

- The consideration of airline-dependent utilisation can be achieved through a configuration optimisation which is overlaid the design synthesis.
- The design range is the prevailing optimisation variable but remains at the same time during the synthesis process a design requirement. Further optimisation variables are those of wing and engines(9).
- Flight profile parameters are also optimisation variables since the flight profile is no longer part of the design specifications but a function of sector length. Considering flight time related costs and fuel costs this profile finally results from the aircraft's actual configuration and performance.
- The merit function is the direct operating costs per seat-kilometre depending on the aircraft's utilisation profile.
- The potential utilisation pattern has to be numerically approximated and included in the design specifications.

Great importance falls to the determination of the flight-profile since it does not only depend on the sector length but also on the aircraft's performance and, thus, strongly interacts with the aircraft configuration. On the other hand it affects the tripfuel requirement. Consequently the determination of the flight-profile demands an iterative procedure. This can be achieved through synthesis-implicit optimisation of the flight-profile on the basis of a pointwise quasi-steady consideration of the aircraft motion. In this way aircraft geometry, performance and flight-profile can be efficiently matched(10).

The described optimisation problem can be solved using the algorithms of non-linear programming available in the CAPDA-system's methods library.

3.2 Application

In order to quantify the impact of different utilisation patterns on optimum design range and operational flexibility a short-, a medium- and a long-haul airliner have been optimized. Their initial baseline designs, as created through CAPDA's initialisation module, are shown true to scale in figure 7.

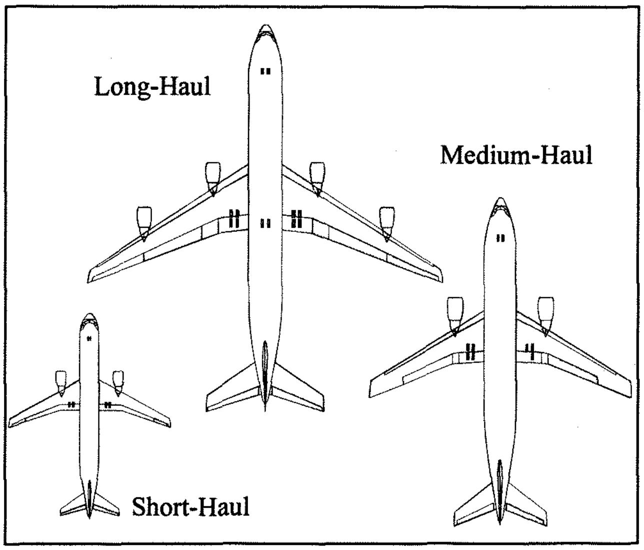

Fig. 7 Baseline Designs.

Since the utilisation profile has become part of the design specifications characteristic utilisation profiles have been defined basing on the evaluation of airline-specific operating patterns. Figure 8 shows exemplarily for the long-haul airliner two profiles and their respective distributions of seat-kilometres. The average sector length of profile A is 3750 km equivalent to 1025 flghts per year while that one of profile B is 5600 km with just 760 flights.

Figure 9 shows impressively the impact of the two utilisation profiles on the aircraft's seat-kilometre costs, dependent on design range and wing aspect ratio. While in the case of profile A the DOC valley is rather flat with the optimum design range at 7000 km the optimum for profile B is well defined at about 9000 km. These results clearly reflect the different development of productivity in figure 8 with the peak of seat-kilometres at stage lengths of approximately 8500 km for profile B.

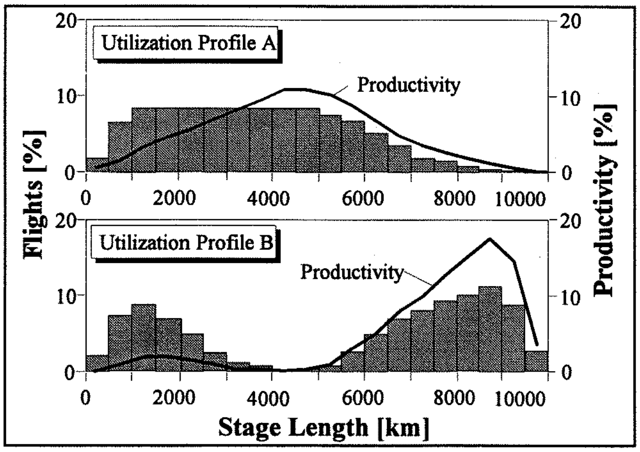

Fig. 8 Utilisation Profiles.

The optimum value of wing aspect ratio also depends on the utilisation profile but to a smaller extent. However, the gradient of DOC with respect to aspect ratio is rather small and largely independent of the utilisation profile. Similar results have been obtained for further design variables, e.g. take-off wing loading and engine bypass ratio.

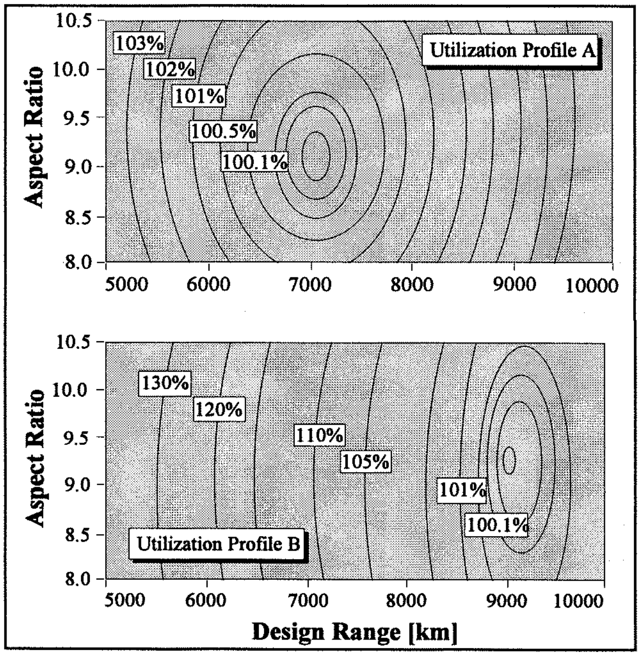

Fig. 9 Topology of Seat-Kilometre Costs.

Assuming similar utilisation profile characteristics for the short-, medium- and long-haul aircraft figure 10 shows for the three configurations a comparable development of optimum design range with growing average sector length. Doubling the fuel price has no significant influence on this result. However, since any average sector length can be associated with a vast number of utilisation profiles there is no clear functional relation between the average sector length and the optimum design range. Here becomes evident that the average sector length is no suitable parameter to estimate the optimum design range.

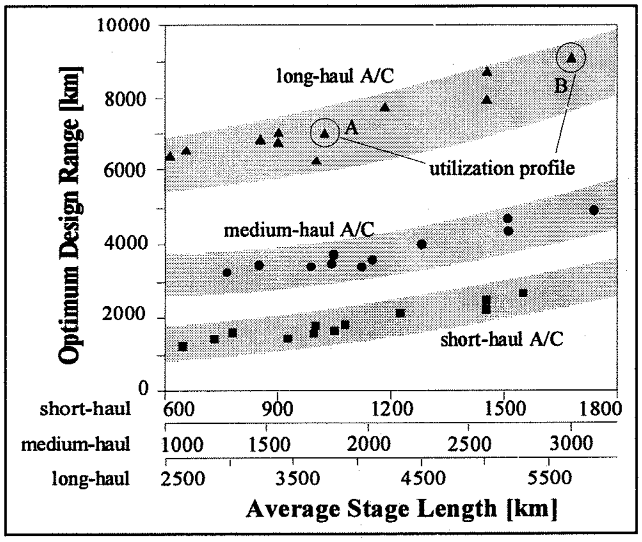

Fig. 10 Optimum Design Range vs. Average Stage Length.

A much more valuable criterion in this respect delivers figure 11 by pointing out that the payload/range capability of the optimum designs covers in general 99% of the required productivity. For utilisation profiles with long average sector lengths this percentage is even higher due to their comparatively high proportion of long stages.

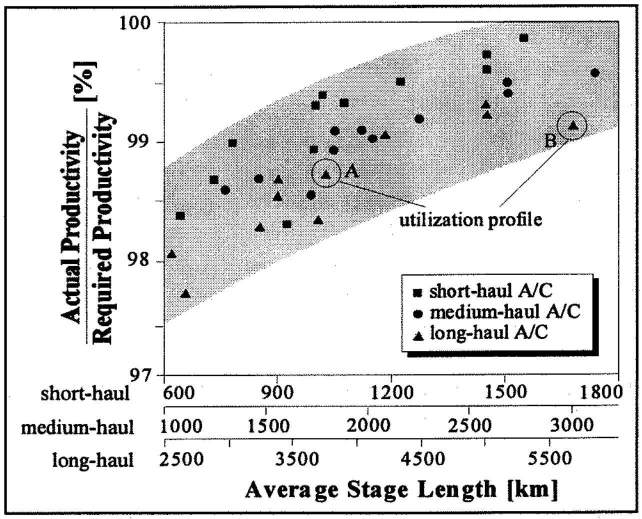

Fig. 11 Optimum Designs. Actual Productivity Related to Required Productivity.

In contrast, in the case of short average sector lengths a compromise between payload capability for longer sectors and low gross weight and consequently low costs for short sector operations must be found. This finally leads to percentages slightly under 99%.

Considering the productivity diagram in figure 8 it can be stated from the design engineer's point of view that a fairly good approach for the optimum design range for a given utilisation profile is that sector length which marks the longest sector to be flown to achieve 99% of the required seat-kilometres. On the other hand, from an airline's point of view which has to acquire its future aircraft, this easily determined optimum design range can be a helpful criterion during the decision-making process for the aircraft to be preferred.

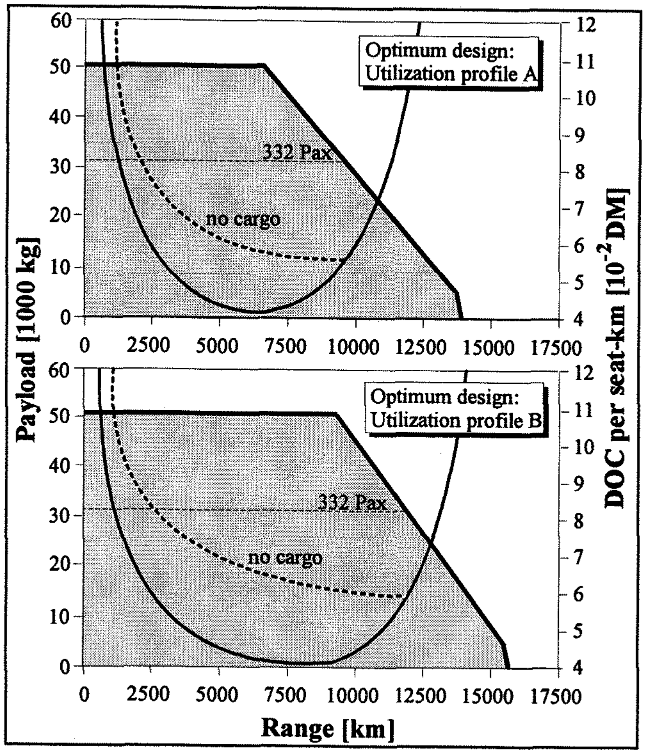

Fig. 12 Optimum Designs. Payload/Range Capability. Seat-Kilometre Costs.

Payload/range capability and development of seat-kilometre costs over range are compared for the optimized long-haul aircraft in figure 12. In order to exemplarily compare the operational flexibility of both airliners the DOC penalty has been calculated which results from the operation of the A-configuration on profile B as well as from the operation of the B-configuration on profile A, figure 13. In this case the B-configuration is the more efficient one because its larger payload/range capability easily balances the disadvantages of its higher maximum take-off weight.

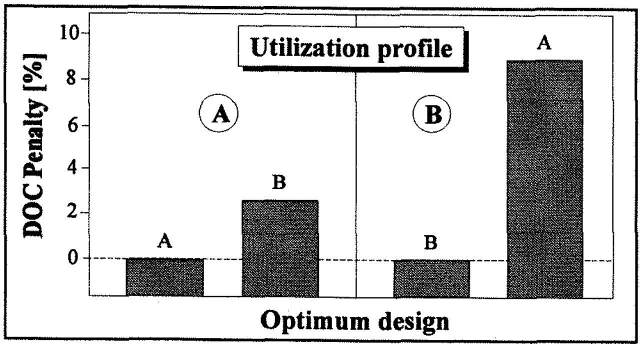

Fig. 13 Operational Flexibility. DOC Penalty.

Summarizing, the presented example shows a significant impact of an aircraft's future utilisation pattern on configuration development.

4 Environmental Aspects

4.1 Strategies

The development of strategies to incorporate environmental aspects into the design process of commercial aircraft has to consider that only little information is available concerning the impact of pollutant emissions on greenhouse effect or ozone depletion and production. Thus, the mathematical modelling of this impact, which would require the consideration of the whole physico-chemical scenario, becomes difficult. In any case, cruising altitude is here of predominant importance since it is besides technological improvements of the engine the most important variable with respect to a reduction of aircraft emissions and their impact on the atmosphere.

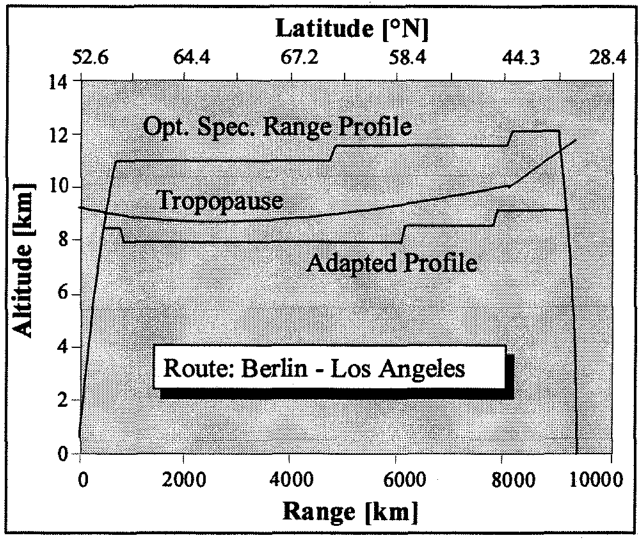

Fig. 14 Ecologically Adapted Flight Altitude Profile(11).

In the classical design process the flight altitude profile of the design mission corresponds to the optimum flight altitude which maximizes the specific range. In order to consider the impact of pollutant emissions on the atmosphere, in a first strategy the specific range has been overlaid by a penalty function which describes the integral impact of all relevant emission products(11). This function is based on the calculation of the actual emission amount per flown kilometre for each pollutant considering the flight altitude, the atmospheric variables of state, the altitude of the tropopause, the geographical location as well as the pollutants' different effects on the atmosphere. The application of this penalty function finally leads to an ecologically defined flight altitude profile, i.e. changed mission specifications which affect the configuration development, figure 14.

A different promising approach to include the environmental impact in the design process can be seen in the modification of the merit function. Referring to the Swedish practice which correlates the landing fees with the specific emissions of the aircraft, this can be performed by defining equivalent operating costs which represent the impact of emissions. For example, penalty functions are conceivable which increase operating costs as function of the cruising altitude to the same extent as pollutants are emitted or the atmosphere is damaged. In the end, the application of the merit function modified in this way leads to an ecologically optimized configuration. Basically, ecological and economic requirements can be matched by the relative importance which is placed to the DOC penalty. Of great interest in this context are penalty fees for long range aircraft which for the most part of the flight operate above the tropopause. On the other hand, very high capacity aircraft may get a bonus due to their comparatively low specific emissions per seat-kilometre.

This brief presentation of two design strategies considering the impact of emissions on the atmosphere gives cause to investigate the role of altitude and speed in more detail.

4.2 Optimisation of Cruising Altitude and Airspeed

A reduction of cruising altitude far below the design altitude causes a significant loss of aircraft performance accompanied by increased fuel consumption and direct operating costs. As an example figure 15 shows the loss of payload/range capability for a typical medium range twin when it operates at lower flight levels.

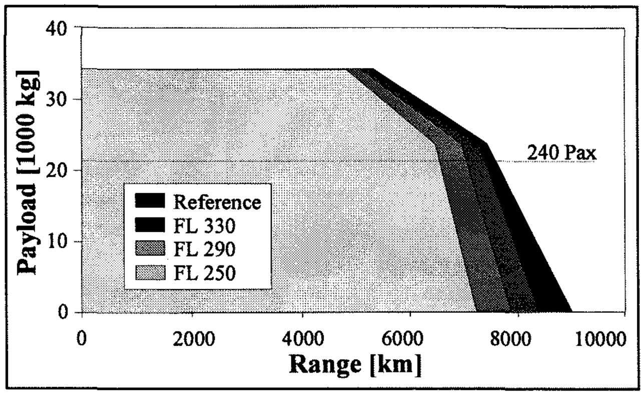

Fig. 15 Payload/Range Capability. Influence of Cruising Altitude.

For a given payload a loss of range of up to 20% will be the consequence. If in future flight altitudes will be restricted to altitudes e.g. below the tropopause which changes with latitude it becomes obvious that only completely new aircraft designs are capable to recover this loss at least partially.

Concept	A	B
Passengers	332 (18F/88C/251Y)	
Cargo	20 t	
Range	7500 km	
Airspeed (Ma/kts)	0.83/485	0.81/485
Operating Altitude	FL 350	FL 250

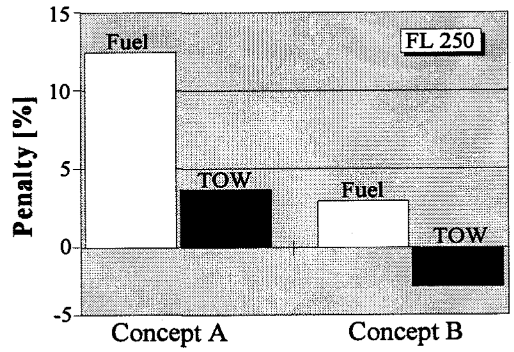

Fig. 16 Configuration Development. Influence of Design Altitude.

This has been evaluated on the basis of a long range quad which is forced to operate in FL 250 (Concept A) and compared with an airliner that a priori has been designed for the lower flight level (Concept B). According to figure 3 the main design parameters of the consolidated baseline design, e.g. aspect ratio, take-off wing loading or engine bypass ratio have been optimized with respect to minimum direct operating costs.

If aircraft A operates in an off-design point in FL 250 tripfuel increases by approximately 12% with a rise in take-off weight of some 2.5%, figure 16. A re-design of the aircraft for the lower cruising altitude cuts down the fuel burn to some 3% higher than that of the original configuration. As a consequence of the smaller sweep angle, wing area and the lighter fuselage due to the lower pressure differential the structural weight decreases. Typical performance charts generated with CAPDA's performance-module, figure 17, show the different performance capabilities of both concepts in more detail.

To practically perform the second strategy which considers the environmental impact within the merit function it becomes necessary to simultaneously optimize the operational variables altitude and speed together with the geometric design variables. In figure 18 the topology of the design space of the long-range aircraft is displayed which results from the parametric variation of cruising speed and altitude. In this example the seat-kilometre costs have been increased by an additional environment-oriented fee which is coupled to the landing and ATC-fees and linearly depends on altitude between 7 km (no additional fee) and 12 km (doubled fees).

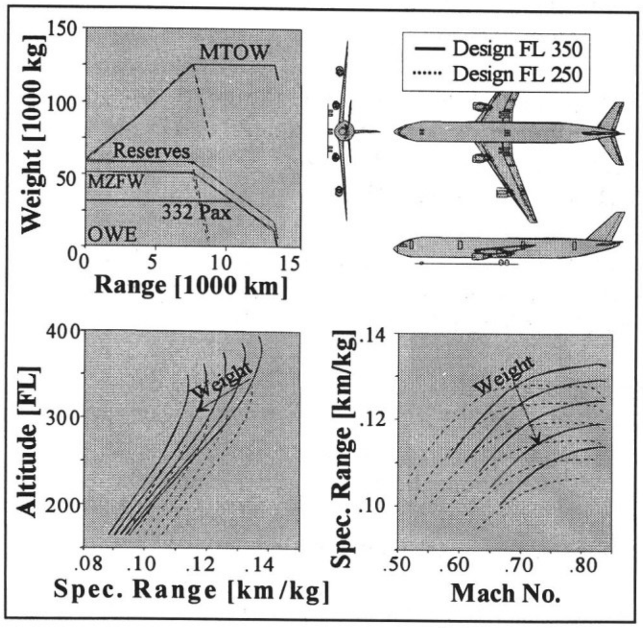

Fig. 17 Typical Performance Charts.

The design space shows a well-defined optimum below typical long range cruising altitudes due to this penalty. With increasing fuel prices the optimum shifts to lower speeds and higher altitudes. In this example for each combination of altitude and airspeed the design synthesis provides different consolidated baseline designs.

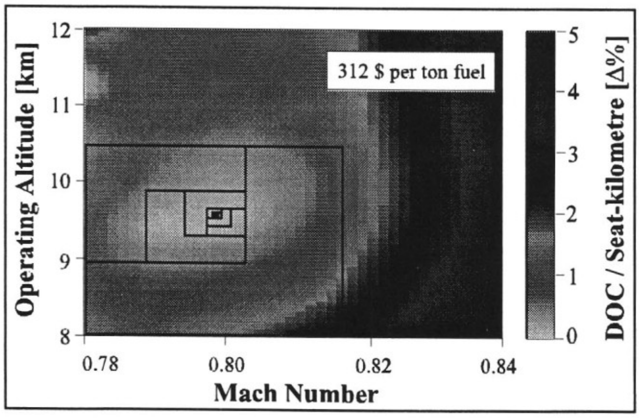

Fig. 18: Optimisation of Airspeed and Cruising Altitude. Topology of the Design Space.

In a next step operational variables (cruising speed, altitude) and geometrical layout (aspect ratio, maximum wing loading) of the same initial baseline design have been simultaneously optimized(12). Starting with the optimisation variable Mach number, the other variables are successively added. Tracing the changes of the optimized variables from step to step the interdependency of operational variables and aircraft geometry becomes evident. Thus the optimisation of cruising speed leads to a slight reduction of the optimum Mach number and a drop of seat-kilometre costs of approximately 2 %, figure 19.

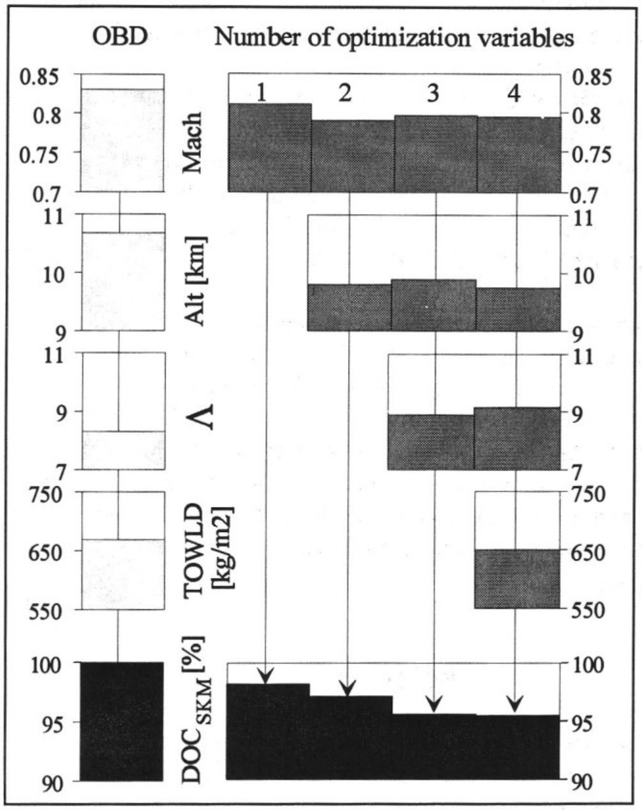

Fig. 19 Simultaneous Optimisation. Operational Variables and Aircraft Geometry. (OBD: Optimized Baseline Design)

This value depends directly on the fuel price, which here is assumed some 20 % higher than the actual one. Adding the cruising altitude to the optimisation variables, an optimum altitude of less than 10 km is obtained. Cruising speed decreases even more to less than Mach 0.80 accompanied by a further percent of DOC-reduction. The simultaneous optimisation of the wing aspect ratio yields - due to a reduction of induced drag - an increase of this ratio from 8.5 to approximately 9; in addition airspeed and cruising altitude rise while operating costs drop by 1.2 %. Introducing finally the take-off wing loading as the fourth optimisation variable a further 0.5 % decrease in operating costs becomes possible. The optimum value for the wing-loading is approximately 20 kg/m^2 lower than the input value, the aspect ratio increases to 9.2 while cruising altitude and airspeed decrease.

The calculations show a significant influence of the variation of cruising altitude and Mach number on configuration development. It becomes obvious that a rearrangement of the aircraft geometry allows to partially recover the performance losses due to the lower flight altitudes.

5 Concluding Remarks

The modular CAE-system CAPDA for computer aided aircraft configuration development was extended to include important aspects such as airline-dependent aircraft utilisation with respect to range as well as flight altitude and speed as variables in the optimisation process. In particular, with this non-linear programming algorithm the basis is established to conceptually design aircraft with respect to specifications which are modified due to 'ecologically'-adapted flight routing and profiles.

The last objective cannot be considered unless atmospheric penalties are quantitatively formulated by atmospheric physicists and chemists. Therefore efforts are in progress to develop strategies to include 3D-flight routing (flight path, altitude and geographic latitude) and to formulate the emission impact on the tropopause in terms of an altitude dependent penalty function which will change the optimum flight altitude and therewith the specific range.

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