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Design Constraints in the Payload-Range Diagram of Ultrahigh Capacity Transport Airplanes

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The economic and productivity potential of ultrahigh capacity airplanes, assessed through the payload-range diagram and the direct operating cost, is considered in the present work from a designer's viewpoint. Two different scenarios are envisaged: first, with current requirements and constraints; second, after including some achievable improvements. The design constraints analyzed are maximum takeoff weight-based wing loading, maximum wingspan, minimum aspect ratio, maximum zero fuel weight-based wing loading, and maximum fuel capacity. Furthermore, to account for possible advantages of unconventional concepts, the common wing-tailplane and a three-surface arrangement are dealt with in parallel, yielding a total of four cases: two configurations in two scenarios. The payload-range diagrams obtained are compatible with very dense, transatlantic, and transpacific routes; however, the three-surface solution in the second scenario exhibits very poor payload vs range flexibility. The benefits of the four cases are considered by computing the direct operating cost relative to that of a B747-400, providing clear economic arguments in favor of these ultrahigh capacity aircraft.

Introduction

THE growing trend in airline passenger demand, together with new routes linking distant regions, is committing airplane designers and manufacturers to face emerging challenges that will shortly lead to airplanes much larger than any one previously designed and built.[1,2] On the other hand, air traffic control is almost overwhelmed (with the subsequent long delays, and safety concerns on flight-path crosses), which certainly supports the need for larger aircraft.

New wide-bodies, like A330, A340, B777, MD11, MD12, appearing in the near future, and the B747 family will momentarily solve the most acute cases. Nevertheless, new, very large aircraft in the 600+ seat class will be required to cope with the aforementioned issues.

Current forecasts on air transport are shown in Fig. 1. The present situation depicts a predominant position of Europe-USA links; in the medium term future it is envisaged that the c.g. will move to the Asia-Pacific region, although the transatlantic routes will still represent a large proportion of the market.[3,4]

Many routes currently using wide-bodies could switch towards ultrahigh capacity aircraft (UHCA). As a matter of fact, above a threshold of some 250,000 passengers (half in each direction), a city-pair link is cost effective. There are several examples involving cities in Western Europe, both North American coasts and the Asiatic Pacific Rim.

On facing a new airplane design one must realize that the development will be subject to three main driving factors[5]: 1) the initial specifications (essentially established by market forecasts), 2) the airworthiness and operation requirements, and 3) the available technology (knowledge and experience). All of these constrain the design scenario.

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Figure 1 provides a starting point in terms of payload and range, taking into account the number of passengers and the geographical situation of some of the country pairs: thus, the aim is a payload above that of the B747-400 for both transatlantic and transpacific ranges.[6]

With respect to airworthiness and operational requirements, the current standards include the 90-s emergency evacuation limit,[7,8] 65 m as maximum wing span,[9] a limit for the airplane noise in the vicinity of airports, appropriate taxiing capability (related to the landing gear track), the airplane height (i.e., the size of maintenance hangars), etc. It is not difficult to foresee that some of these requirements will change in the near future to more severe values, while others will ease. For example the 65-m limit might be enlarged up to 80 or more meters, for main international airports. It must be recalled that some infrastructure modifications were already needed with the introduction of B747. Among the aforementioned requirements, only the wingspan limit will be included in this article, due to its strong influence on the payload-range diagram.

Finally, the available technology imposes diverse constraints on the designer (wing loading, aerodynamic efficiency, wing aeroelastic behavior, etc.) that are continuously evolving and being improved through scientific and applied research effort.

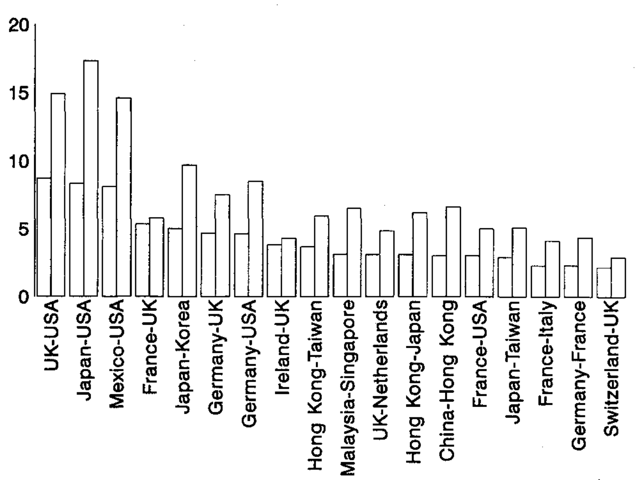

Fig. 1 Main country pairs in medium term air traffic forecast. Millions of passengers in 1991 and 2001.

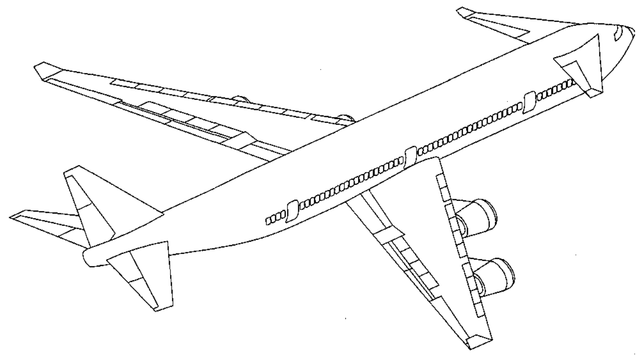

Fig. 2 Perspective view of a three-surface airplane.

This article is aimed at assessing the economic and productivity possibilities (through the payload-range diagram and the direct operating cost) of future ultrahigh capacity airplanes, designed in two different scenarios: first, with current requirements and technological constraints; second, taking into account some achievable improvements.

As the design environment is changing, some unconventional configurations could find a place on the desk. Many designs (even some astonishing ones) have been proposed for different missions.[10-12] One such unconventional concept is the three-surface solution,[13] depicted in Fig. 2 as a large airplane with canard, wing, and horizontal stabilizer. Literature shows that such a solution is both feasible and efficient.[13-15] Consequently, the classical wing-tailplane as well as a three-surface configuration will be dealt with in parallel in the present study, yielding a total of four different cases.

Payload, Range, and Maximum Takeoff Weight

Let us first establish some simple relations for the main aircraft weights. The range equation states, within the initial design accuracy, that[5]

$$R = K \ln \frac{\text{MTOW}}{\text{MTOW} - \text{TFW}} \tag{1}$$

where R is range, K the range parameter from Breguet's equation, MTOW the maximum takeoff weight, and TFW the amount of fuel burnt during the trip.

On the other hand, from the definition of the main weights

$$\text{MTOW} = \text{OEW} + \text{PL} + \text{TFW} + \text{RFW} \tag{2}$$

where OEW is the operating empty weight, PL the payload, and RFW the additional fuel weight needed for diversion and loiter.

Equations (1) and (2) can be rearranged as

$$\text{PL} = \text{MTOW}\left[\left(1 - \frac{\text{RFW}}{\text{LW}}\right)e^{-R/K} - \frac{\text{OEW}}{\text{MTOW}}\right] \tag{3}$$

where LW indicates landing weight.

This equation establishes a link among several variables and parameters. Some of them are known from existing aircraft (e.g., the ratio OEW/MTOW); nevertheless this is not the case for the maximum takeoff weight. It must be computed from payload and range specifications, but it is otherwise limited by diverse constraints: maximum wingspan accepted by airport authorities, minimum aspect ratio to reach a given K, and maximum wing loading W_{to}/S for strength and stiffness considerations. In closed form that implies

$$\text{MTOW} \leq (W_{to}/S)_{max}(b^2_{max}/A_{min}) \tag{4}$$

Typical values from the present day scenario are b_{max} = 65 m (213 ft), and W_{to}/S = 7500 Pa (156 lb/ft²). Folding wingtips have not been considered here for the increase in empty weight and direct operating cost.[16] On the other hand, to reach a desirable figure for the range parameter, say K = 27,000 km, a minimum value of L/D = 17 is needed, which yields[17] A_{min} = 7. Larger aspect ratios must be avoided since they lead to smaller wing areas (for a given value of wingspan). All in all, that provides a limit for MTOW of roughly 460,000 kg (1,015,000 lb). Such an ultrahigh capacity airplane is the largest one that can be produced with current limitations and conventional configuration (while still retaining an efficient design). The argument may be completed by OEW = 0.45MTOW and RFW = 0.07LW, to define a limit for the payload-range diagram, as depicted in Fig. 3. The corresponding diagram for B747-400 is also shown for comparison.

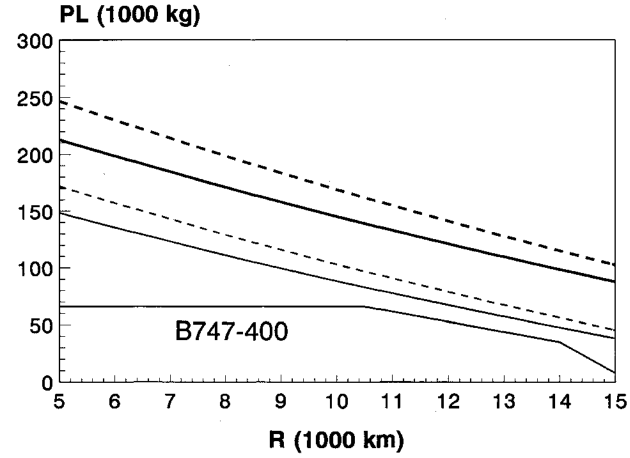

Fig. 3 Iso-MTOW lines as limits in the payload-range diagram, for the four cases under consideration: —— conventional configuration and current technology; ---- three-surface arrangement and current technology; ——— conventional configuration in future scenario; ▪▪▪▪ three-surface aircraft in future scenario.

It is important to realize that the limit imposed by the maximum takeoff weight corresponds to the segment of higher commercial interest in the PL-R diagram; particularly for long-range aircraft.

As indicated in the Introduction, this process will be repeated for a three-surface aircraft. Most relevant figures still apply, but in this configuration the wing is only responsible for about 85% of total lift[13]; obviously, the canard and tailplane do not have the same surface loading as the wing does, and must be sized properly. Thus, a new MTOW is computed: 541,000 kg (1,190,000 lb). Due to its better trimming,[13,15] the three-surface design will exhibit a somewhat higher L/D; say to imply K = 28,000 km. Finally, the presence of a canard will probably require some additional weight (structure, hydraulics, other systems, etc.), pushing the OEW/MTOW ratio up to 0.46. Following an earlier procedure, it is possible to trace the appropriate limit in the payload-range diagram, shown in Fig. 3.

Let us now jump ahead in time to a future scenario with improved technology and more relaxed constraints. With a sound extrapolation our new parameters could be, e.g., b_{max} = 75 m (246 ft), W_{to}/S = 8500 Pa (177 lb/ft²), and OEW/MTOW = 0.42. Considering a more efficient cruise, with K = 31,000 km, and a lower specific fuel consumption, the aspect ratio becomes A = 8.5. The situation for the three-surface aircraft is analogous, with corrected values of OEW/MTOW = 0.43 and K = 32,000 km. Both cases are also depicted, as future limits in the payload-range diagram, in Fig. 3.

An interesting feature of these results is the position of the maximum productivity in terms of payload times range (passenger-miles or ton-miles) for all four airplanes. The corresponding points are, as shown in Fig. 4, at around 8900 km (4800 nm) for the two airplanes designed under current rules, 11,100 km (6000 nm) in the conventional design but future

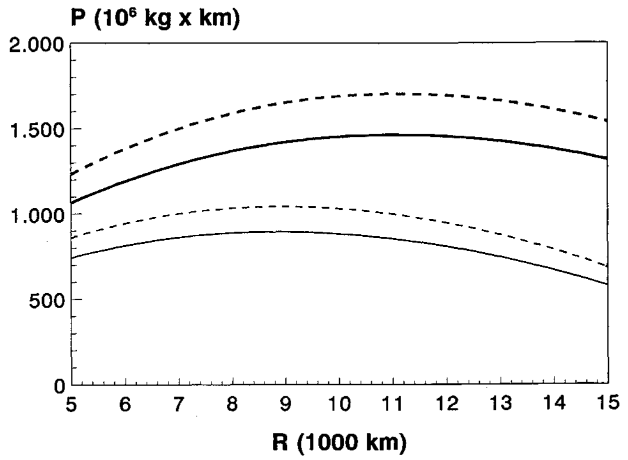

Fig. 4 Theoretical productivity (payload times range) of the four cases. Interpretation of lines as in Fig. 3.

scenario, and more than 11,200 km (6100 nm) for the most extreme case. Meanwhile, the last two aircraft are accurately matched to transpacific routes, the first two cases lie between transpacific and transatlantic stages; some additional comments will be devoted to such a fact later on.

On the other hand, it is noticeable that the point of maximum productivity of the B747-400 (some 8700 km, or 4700 nm) corresponds to a range shorter than any of the two kinks in its PL-R diagram (see Fig. 3). This is so because its maximum payload is then limited by maximum zero fuel weight, when the wing is not alleviated by fuel loads.

Maximum Zero Fuel Weight Limitations

It is clear that the maximum takeoff weight can be limited either by structural considerations or by certain performance requirements, although in the previous paragraph it was assumed that W_{to}/S was the main constraint. On the other hand, in most cases the wing is designed to support the loads at some critical maneuver or during gusts. Depending upon the spanwise position of fuel tanks and the arrangement of wing structure, it may happen that the wing bending moment at maximum zero fuel weight (MZFW) rises as a new design constraint, implying operating limitations even below those determined by MTOW. If this is so, the payload-range diagrams depicted in Fig. 2 should be cut at some maximum payload (MPL) level. The MZFW is defined as

$$\mathrm{MZFW} = \mathrm{OEW} + \mathrm{MPL} \tag{5}$$

With the aforementioned requirements, Eq. (5) can be rewritten as

$$\mathrm{PL} \leq (W_z/S)_{\max}(b_{\max}^2/A_{\min}) - \mathrm{OEW} \tag{6}$$

In this equation, W_z/S is the wing loading based on maximum zero fuel weight, and OEW must be determined from the parameter OEW/MTOW and the actual value of MTOW.

Equations (2), (3), and (6) provide a new relation among the relevant variables and parameters in the following way:

$$\mathrm{PL} \leq (W_z/S)_{\max} \frac{b_{\max}^2}{A_{\min}} \left[1 - \frac{\mathrm{OEW/MTOW}}{(1 - \mathrm{RFW/LW})} e^{R/K}\right] \tag{7}$$

where LW is the landing weight; i.e., OEW plus PL plus reserve fuel.

It must be realized that this curve is not a part of the payload-range diagram, but a locus of points defining the new MZFW limit. Its intersection with the analogous MTOW limit marks the value of MPL. Consequently, when the structural limit is determined by MZFW (as it is commonly the case), it is not possible to design the airplane with segments of PL-R diagram on the upper left side of Fig. 3. This can be clearly seen by comparing the PL curves in Figs. 3 and 5.

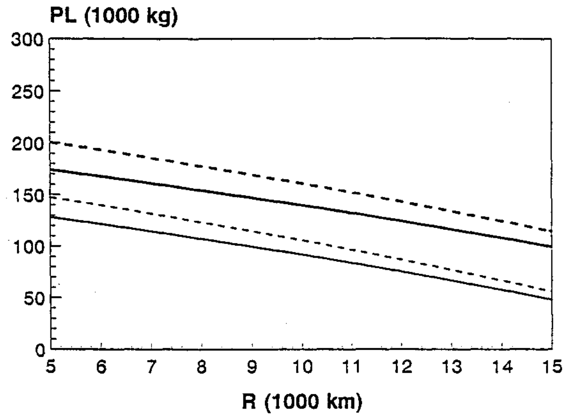

Fig. 5 Iso-MZFW lines as limits in the payload-range diagram. Interpretation of lines as in Fig. 3.

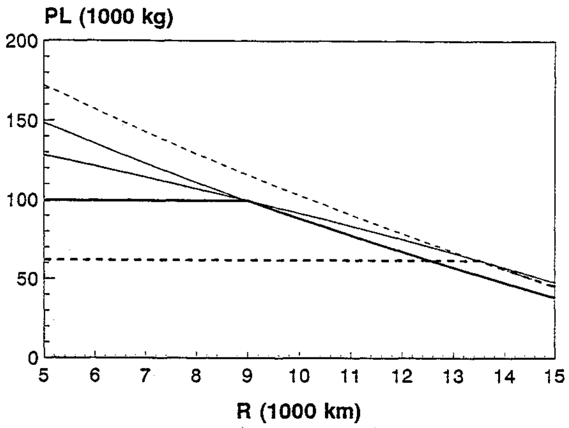

Fig. 6 Example of payload-range diagrams of two airplanes with same MZFW, but different MTOW, showing differences in productivity and route adequacy.

The values used to depict the iso-MZFW curves are W_z/S = 5000 Pa (104 lb/ft^2) for present day technology, and 5500 Pa (114 lb/ft^2) for the future envisaged scenario.

Equation (7) can be interpreted in a different way: on moving to the right along iso-MZFW curves, higher MTOW values are required. This may sound unrealistic, but it is true up to the point where a new boundary appears: e.g., takeoff field length for a given thrust, or landing field length, etc. If some relaxation is possible on such performance limitations, Eq. (7) may be used to understand the available space for the design.

Figure 6 exhibits the payload-range diagrams of two aircraft with the same MZFW, but different MTOW. Key factors in the design process, at conceptual or preliminary level, are the density of the routes to be served (without forgetting the enormous freighthold volume associated to those aircraft), the productivity (in terms of passenger-miles or ton-miles offered), and the direct operating cost.

Limitation Due to Fuel Capacity

Fuel capacity appears as another operating limitation, as a second kink in the payload-range diagram. This constraint is particularly relevant for long-range aircraft.[5] Fuel tanks occupy a fraction of wing volume, although in some aircraft an auxiliary tank is provided in the tailplane. Consequently, the present model takes the maximum fuel capacity as

$$\mathrm{FC} \approx k\frac{S^2}{b}\frac{t}{c} \approx k\frac{b^3}{A^2}\frac{t}{c} \tag{8}$$

where t/c is an average relative thickness of the wing.

The constant k and the relative thickness in Eq. (8) can be determined from existing long-range aircraft; so k times t/c is roughly equal to 0.046 if the International System of Units is employed. Moreover, fuel density is also known (about 800 kg/m^3). Thus, given the maximum wingspan and the aspect ratio, the maximum fuel weight is obtained. Accordingly, from Eq. (1), and the fact that reserve fuel is around 7% of the landing weight, a new limitation in range must be marked in the payload-range diagram, as shown in Fig. 7. With data already known from previous paragraphs, the limits are, in the usual order of cases, at R = 13,500 km (7300 nm), 11,100 km (6000 nm), 12,000 km (6500 nm), and 9900 km (5400 nm). The last result is worthy of further comment.

From Fig. 5 it can be seen that the three-surface aircraft designed in the future scenario has a MPL limit at around 145,000 kg (319,000 lb), paired to a range of 11,700 km (6300 nm), which corresponds to the first kink in the payload-range diagram. Now, it appears that the new fuel capacity limitation (second kink) does not allow operations, starting at MTOW, over longer distances than 9900 km. The simultaneous accomplishment of both boundaries implies a physical impossibility, within the described model and limitations. Auxiliary tanks may partly solve the problem; canard and tailplane may provide some 10% of additional volume that would push the limit up to 11,300 km (6100 nm), very close to the MZFW limit of 11,700 km.

Even considering that both figures are equal, within the initial design accuracy, the segment of commercial interest in the payload-range diagram (corresponding to taking off at MTOW), has collapsed to a point. Such a design is extremely poor from the productivity viewpoint, since it does not allow any flexibility in payload-range pairs: the theoretical productivity curve (payload times range) of this case has become very sharp, implying severe economic losses that are particularly remarkable for transatlantic routes (see Fig. 8).

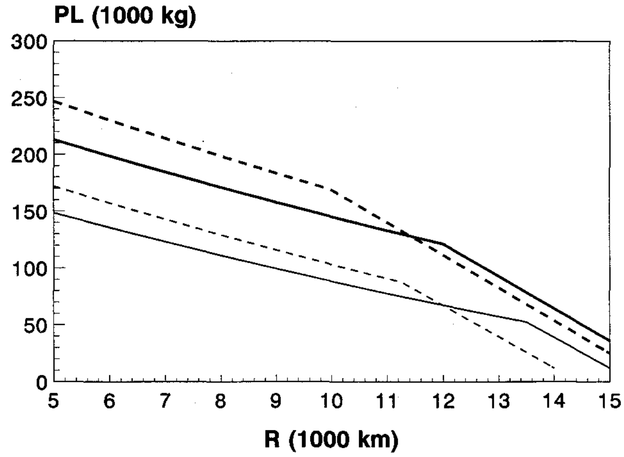

Fig. 7 Effect of limitation due to fuel capacity on iso-MTOW lines. Interpretation of lines as in Fig. 3.

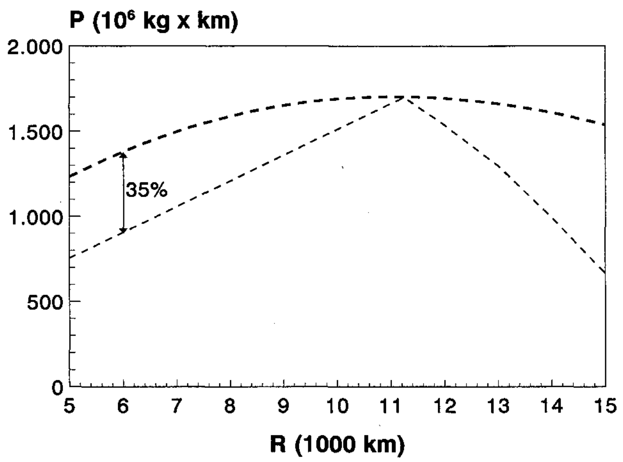

Fig. 8 Theoretical (bold line) and real productivity (payload times range) of the three-surface airplane with future scenario constraints.

Economic Assessment

The economic efficiency of the aforementioned cases can be evaluated through the direct operating cost (DOC) associated with each configuration-design scenario pair. DOC has been computed using methods found in the literature.[18–21] The main components are crew, fuel and oil, insurance, maintenance, depreciation, navigation and landing taxes, and finance costs, i.e.,

$$\mathrm{DOC} = \mathrm{DOC}_{\mathrm{crew}} + \mathrm{DOC}_{\mathrm{flol}} + \mathrm{DOC}_{\mathrm{ins}} + \mathrm{DOC}_{\mathrm{maint}} + \mathrm{DOC}_{\mathrm{depr}} + \mathrm{DOC}_{\mathrm{nav}} + \mathrm{DOC}_{\mathrm{fin}} \tag{9}$$

The purpose of the present assessment is not to determine the exact value of DOC, but to perform a comparison between each case and the B747-400. With this objective in mind, the problem can be linearized leading to the following simplified expressions:

$$\mathrm{DOC}_{\mathrm{crew}} \sim \mathrm{MTOW}^{\alpha} \tag{10a}$$

$$\mathrm{DOC}_{\mathrm{flol}} \sim \mathrm{MTOW}(1 - e^{-R/K}) \tag{10b}$$

$$\mathrm{DOC}_{\mathrm{ins}} \sim \mathrm{MTOW}^{\beta} \tag{10c}$$

$$\mathrm{DOC}_{\mathrm{depr}} \sim \mathrm{MTOW}^{\beta} \tag{10d}$$

$$\mathrm{DOC}_{\mathrm{nav}} \sim \mathrm{MTOW}^{\gamma} \tag{10e}$$

$$\mathrm{DOC}_{\mathrm{fin}} \approx 0.07\mathrm{DOC} \tag{10f}$$

Maintenance costs can be split into two different contributions: one corresponding to airframe and equipment; another to the powerplant. In the present model it may be expressed as

$$\mathrm{DOC}_{\mathrm{maint1}} \sim k_{\mathrm{compl}}\mathrm{MTOW}^{\beta} \tag{10g}$$

$$\mathrm{DOC}_{\mathrm{maint2}} \sim k_{\mathrm{eng}} T_{\mathrm{to}}^{\delta} \tag{10h}$$

Obviously, these equations are only valid for comparison purposes when the same range, block speed, and annual utilization are used. The exponents α, β, γ, δ are selected to fit values proper of very large aircraft. k_{compl} (slightly larger than 1) represents a parameter to account for extra complexity of the three-surface arrangement. In a similar way, k_{eng} (also slightly larger than 1) is included, because the two biggest airplanes could need six engines instead of four.

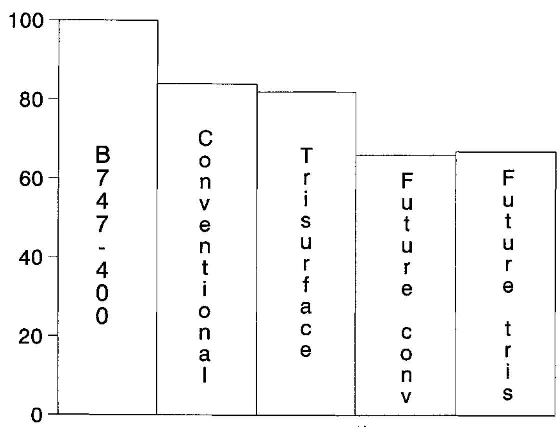

Fig. 9 Direct operating cost of the four cases considered, relative to B747-400.

Taking an initial breakdown of DOC from published data on the B747,[22,23] and applying Eqs. (9) and (10) to the four cases under consideration, the relative DOCs are obtained. To avoid problems with the lack of flexibility of the largest aircraft (see Fig. 8), the transpacific range of 11.000 km has been considered. Moreover, the number of passengers has been chosen in accordance to the maximum payload, regardless of the required size and internal arrangement of the fuselage. Among partial results, fuel cost per seat-mile shows very little variation, in agreement with some reported data.[6]

The values obtained by means of the former model (namely 84, 82, 66, and 67%, as indicated in Fig. 9) may be interpreted as conservative but, nonetheless, they represent a relevant decrease from the original baseline. The complexity associated with the three-surface configuration is clearly penalized in the above results; particularly in the largest aircraft by both its complexity and the need of special powerplant.

Conclusions

Ultrahigh capacity aircraft are necessary due to the future growth of air transport. Most of the technology required to design these giant aircraft is already available, although some current limitations must be removed to allow a meaningful increase in payload capacity. Under the scope of the present work, the most constraining factors are the wingspan limit imposed by on-airport maneuverability, and the wing loading based on maximum zero fuel weight. The payload-range diagrams obtained in the current and an achievable scenario are compatible with very dense, transatlantic, and transpacific routes. The potential benefits, in terms of DOC, are more than enough to balance the financial and technological problems of these ultrahigh capacity aircraft. Some unconventional configurations, like the three-surface airplane, could find a place among the possible designs.

Acknowledgments

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