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# On the preliminary design of PrandtlPlane civil transport aircraft

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## Abstract

In the future, novel aircraft configurations will be needed in order to cut noxious emissions and noise and to face the increase of traffic all over the world. This paper presents procedures and tools adopted for the preliminary design of an innovative civil transport aircraft conceived according to the Prandtl's Best Wing System concept and known also as "PrandtlPlane". The lifting system is optimized by means of an in house code in the subsonic range, followed by two calibration steps to take the transonic effects into account; it results a trade-off between subsonic and transonic regimes, up to the final optimization at transonic cruise speed and the design of control surfaces in approach conditions. The reference aircraft examined in this paper is a PrandtlPlane with a span limited to 36m, the same of Airbus A320 and Boeing 737, in order to be categorized according to ICAO Aerodrome Reference Code C standard; instead, the capacity of this aircraft is increased to about 320 passengers, typical of upper category aircraft, with the design of a two aisles cabin. Some details are given about the design criteria of the fuselage and a brief description is given about the lifting system design procedure at transonic cruise speed and the aerodynamic controls at low speed.

## 1 Introduction

The new requirements on future air transport, both in the USA and Europe, can be summarized as follows:

- to satisfy the increase of air traffic with more safety and more comfort of flight;
- to cut emissions and noise per unit of transport;
- to reduce time for ground operations.

Further requirements could regard the design of future aircraft with new fuels and/or with distributed electric or hybrid propulsions. In the next two decades the air traffic will nearly double with respect to today, especially in medium and small airports due to the increment of the point-to-point connections; at the same time, only very limited new airport areas will be available and, according to the recent ACARE requirements on a greener and safer transport aviation, the transport improvement of the next generation aircraft could not occur without a cut of emissions and a strong reduction of noise. The previous challenges will never be fulfilled by adopting conventional airplanes, because they have grown up to their maximum potential and further significant improvements of their efficiency are no longer possible.

New aircraft configurations have been proposed in order to satisfy these requirements: the candidate configurations for future aviation are based on Blended Wing Body (BWB), Truss Braced Wings (TBW) and PrandtlPlane (PrP) concepts.

Figure 1: Blended Wing Body (BWB), Truss Braced Wings (TBW) and PrandtlPlane (PrP) concepts

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The Blended Wing Body (Figure 1, left), next to some possible benefits [1], presents some critical drawbacks. More in particular, a BWB solution is possible only in the case of large span aircraft; generally speaking, the aerodynamic efficiency of a BWB is not the best possible for a given span and total lift; the challenges of more safety and comfort in flight are critical aspects as, for example, safety during emergency evacuation, flight comfort during roll manoeuvres, lateral control and flight stability; the time for the ground operations is a further critical aspect; the airport infrastructures are not conceived for this aircraft configuration. BWB configuration is less flexible also in terms of integration of distributed electric or hybrid propulsion systems.

The Truss Braced Wings concept (Figure 1, middle) aims at reducing the induced drag by improving the overall span of a conventional monoplane: the consequent structural and aeroelastic disadvantages are resolved by connecting the wings to the fuselage by means of struts. The aerodynamic advantage of the TBW configuration is the reduction of induced drag, and the drawbacks are aerodynamic interference and reduction of the speed of maximum efficiency. In the case of the structural design, aeroelastic effects could produce a weight penalty. In any case, the overall aircraft span becomes prohibitive where very large capacity is required. Finally, the TBW configuration becomes incompatible with ICAO Aerodrome Reference Code C standard ([2]), hence it cannot be considered an alternative to conventional aircraft of the class of Airbus A320 or Boeing 737.

The PrP configuration (Figure 1, right), presents the minimum induced drag among all the solutions available (as shown by Prandtl in 1924 [3] and proved in [4]); the cabin services and the emergency evacuation procedures are the same (well proven) of the conventional aircraft; thanks to the single and continuous cargo deck, the time for loading and unloading cargo can be reduced compared with the conventional solutions; a PrP has positive lift on both wings and is stable in any flight condition; the stall speed is lower than any equivalent monoplane; stall is very smooth; pitch control acts as pure couple and is efficient and safe; freight capability is higher than that of today airplanes owing to an innovative cargo bay design; many engine integration solutions are possible; aeroelastic effects can be controlled without great weight penalties. Compared to traditional aircraft, a PrP even with a lower wingspan of a conventional one, can provide the same aerodynamic efficiency and improve the payload capability well beyond the today limits.

This paper aims at presenting the preliminary analyses for the design of PrP configurations, carried out at Pisa University. In particular, these design tools are applied to the design of a new aircraft in the framework of the project PARSIFAL ("Prandtlplane ARchitecture for the Sustainable Improvement of Future AirpLanes", [5]), funded by the European Community in the framework of Horizon 2020 and coordinated by the University of Pisa (Italy). Other partners of PARSIFAL project are Delft University of Technology (Delft, Netherlands), ONERA (Meudon, France), ENSAM (Bordeaux, France), DLR (Hamburg, Germany), SkyBox Engineering (Pisa, Italy).

The solution proposed in PARSIFAL is the PrP configuration applied to civil transport aircraft with a span of 36 metres (the same of A320 and B737), and to transport about 320 passengers as the superior category aircraft; in this way, the air traffic could be improved without limitations in all the airports, including the ICAO Aerodrome Reference Code C ones. The payload capacity of a PrP can be increased by means of a proper design of the fuselage (more details are given in the following); due to the higher aerodynamic efficiency, emissions can be cut during cruise and, mainly, during the take-off and landing phases, where the induced drag is maximum in percentage of the total drag and noise is minimized correspondingly; the safety of flight is enhanced due to the following main factors: smooth stall and easy recovery from stall and pitch control actuated with a pure couple without modifying the total lift during manoeuvres; ailerons positioned on both the wing tips with the consequent maximum roll efficiency and more safety due to the command duplication. The box wing, over-constrained to the fuselage, is a natural damage tolerant structure. Many results confirm that a typical feature of a PrP is the comfort during flight, due mainly to the very high pitch damping. The time required for ground operations can be reduced thanks to a single and continuous cargo deck with multiple doors on both front and rear. The PrP configuration allows adopting different propulsion system solutions (including, for example: liquid hydrogen or methane as fuels, electric propellers distributed along both the wing span). The PrP configuration can be adopted for aircraft of any type and category, from 2 seats, as previously investigated in[6], to ultra large airliners, from low to very high transonic speeds, from passenger to freighter aircraft ([7]). A general overview on box wing configuration is reported in [8].

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In this paper, only the following main aspects are addressed: the design criteria of the fuselage, the preliminary aerodynamic design of the lifting system in the transonic cruise condition and the design of control surfaces at low speed.

## 2 Preliminary sizing of the fuselage

With reference to PARSIFAL project, the possibility to carry a number of passengers not lower than 250 and, at the same time, to maintain the overall dimensions of aircraft like A320 or B737 requires the adoption of twin aisles fuselages, in order to embark a greater number of passengers compared to the reference conventional planes. In this phase of conceptual design, two different layouts for the cabin section have been identified: the first one with 8 seats abreast, in a 2-4-2 disposition (Figure 2, a), and the second one with 10 seats abreast, in a 3-4-3 disposition (Figure 2, b); assuming preliminarily a seat pitch equal to 29 inches for a high density passenger compartment, it is possible to set a maximum of 32 seat rows, thus achieving 256 and 320 passengers, respectively, for the two proposed solutions.

The cargo vain is sketched to house LD3 and LD1 standard containers respectively, and is capable to satisfy the minimum necessary volume requirements for luggage transport; furthermore, the volume available for the overhead bins is adequate to satisfy the requirements.

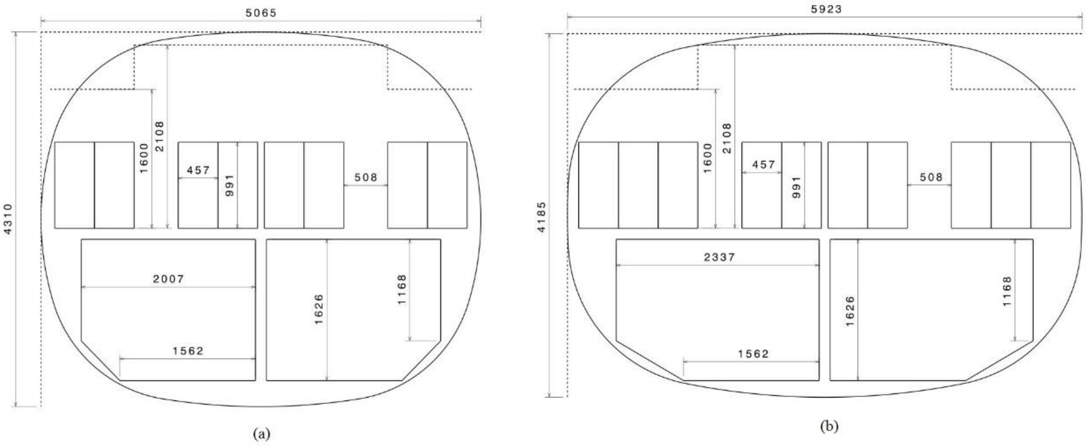


Figure 2: Sketch of two cabin section layouts for Parsifal Project

In this conceptual design stage, the adoption of non-circular fuselage cross sections is proposed; such sections are composed of circular arches, tangent each other and with different curvatures, designed in order to minimize the wet surface and, consequently, the friction drag; furthermore, these solutions provide a larger fuselage width in the aft zone, which is useful to support the connection with the empennage, made of two fins (in order to prevent the flutter of the wing system). The high width of the fuselage section allows also to allocate the main landing gears on its sides, inside two sponsons with limited transversal dimensions; the main landing gears are allocated laterally without any interference with the cargo bay. The sketched solutions are a first guideline for the following detailed design, which must take some constraints into account, like the necessity to provide space for wires and systems as, for example, electric cables, air and hydraulic pipes. Figure 3 shows an outline representation of the internal boundaries of the minimum wetted surface solution described before .

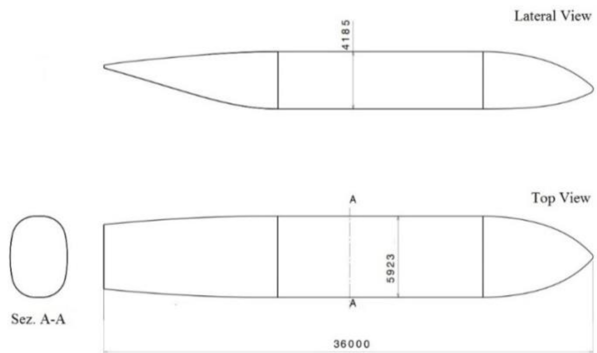


Figure 3: Lateral view and top view of a 3-4-3 configuration

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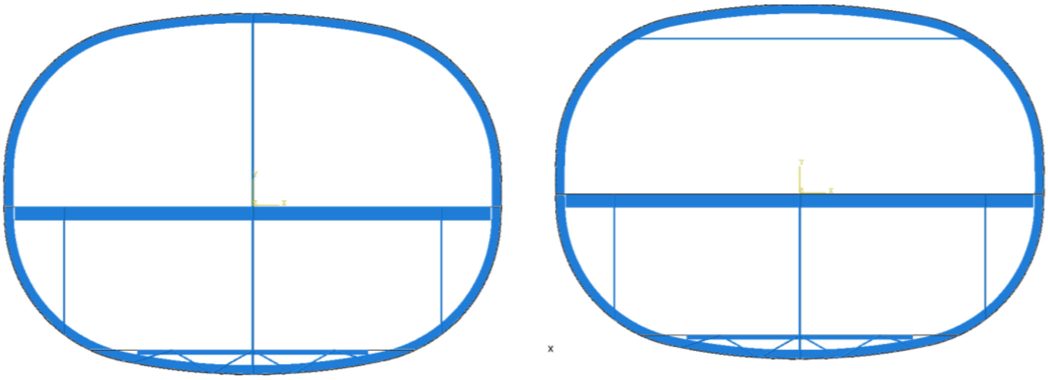
A new concept for the design of the fuselage cross section also is accomplished by innovative structural solutions; it is under study the possibility to connect the upper and lower part of each fuselage frame by means of a vertical truss, made in composite, which undergoes tension when pressurization loads are applied (Figure 4, a); this solution reduces significantly the empty weight of the fuselage structure. Another solution under study is to position a stiffening crossbeam in the upper part of the frame (Figure 4, b) , or a combination of the two solutions. In both solutions, a central support is introduced under the floor beam.



(a) (b)

Figure 4: Possible fuselage cross section schemes: solutions with vertical truss (a) and horizontal crossbeam (b)

The introduction of these new concepts for the fuselage design leads to the immediate advantage of carrying a bigger number of passengers compared to aircraft of the same category and with the same overall dimensions; another benefit is the possibility to have a continuous cargo deck, by positioning the front wing of the lifting system properly: in this way, it is possible to load and unload luggage and goods in a faster and more efficient way compared to the present procedures. The possible drawbacks of this fuselage configuration are mainly related to the current uncertainty to obtain better global performance in terms of costs, compared to conventional solutions.

The main landing gears under study are mounted laterally in the fuselage, without intersections with the cargo vain and with a minimum aerodynamic impact of the sponsons. The solution adopted, together with the large passenger deck, would allow to provide the aircraft with built-in airstairs.

## 3 Conceptual design process: high speed aerodynamics

In the conceptual stage of the design process it is necessary to evaluate the largest possible number of configurations with reduced computational cost, in order to detect the most relevant trends between performances and design parameters, and to identify a group of initial configurations for the following detailed analyses. A low fidelity design methodology has been defined in this context; it is based on an optimization process calibrated on the main requirements of the aircraft and the analyses have been carried out with an in-house code (*Aerostate*). The constrained optimization process is related to the cruise flight condition in order to obtain the lifting systems' planform of a series of configurations. The mathematical formulation, is the following:

$$\begin{cases} \min\left(-\frac{L}{D}(\boldsymbol{x})\right) \\ W_{des}-\varepsilon \le L(\boldsymbol{x}) \le W_{des}+\varepsilon \\ SM_{min} \le SM(\boldsymbol{x}) \le SM_{max} \\ \left(\frac{W}{S}\right)_{min} \le \left(\frac{W}{S}(\boldsymbol{x})\right)_{wing} \le \left(\frac{W}{S}\right)_{max} \\ \max\left(c_l(y)\right) \le c_{l_{max}} \\ \lambda_{bay} < 1 \\ lb < \boldsymbol{x} < ub \end{cases}$$

where the first expression defines the minimization of the objective function (-L/D), corresponding to the maximization of the aerodynamic efficiency in cruise condition, $\boldsymbol{x}$ is the optimization parameters vector, whose

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components can vary into the design space defined by lower boundaries ($lb$) and upper boundaries ($ub$), and the other expressions are the constraints imposed into the process. In particular:

- the lift $L(\boldsymbol{x})$ must be equal to the design weight $W_{des}$ (with a tolerance $\varepsilon$), in order to satisfy the vertical equilibrium;
- the static margin of stability $SM(\boldsymbol{x})$ must be in a prescribed range, in order to obtain longitudinally stable as well as manoeuvrable configurations;
- the wing loading of every lifting surface $\left(\frac{W}{S}(\boldsymbol{x})\right)_{wing}$ must be within a range fixed by the designer;
- the local $c_l$ of every section of each wing cannot exceed a threshold value $c_{l_{max}}$;
- the taper ratio of each wing bay $\lambda_{bay}$ must be lower than 1.

The design parameters define completely the lifting system (chords, twists, sweep angles, dihedron angles, limits for the longitudinal position of lifting surfaces); the span is fixed to 36 meters (the maximum value for ICAO Aerodrome Reference Code C compatibility). The weight estimations and the longitudinal position of the centre of gravity, for every configuration, are conducted with first-approximation methods, whereas the aerodynamic evaluations are carried out with the Vortex Lattice Method code *AVL*. This solver has been chosen for the very low computational time required for each aerodynamic calculation; however, potential methods are not able to consider compressibility effects, in term of drag increase due to the presence of shock waves on the airfoils: consequently, it has been necessary to calibrate the whole design procedure by means of a series of increasing-fidelity analyses, with the aim of taking these transonic effects into account.

The first calibration of constraints and boundaries of the design space has been carried out with a low-fidelity model which needs very low computational times; a scheme of this model is presented in Figure 5.

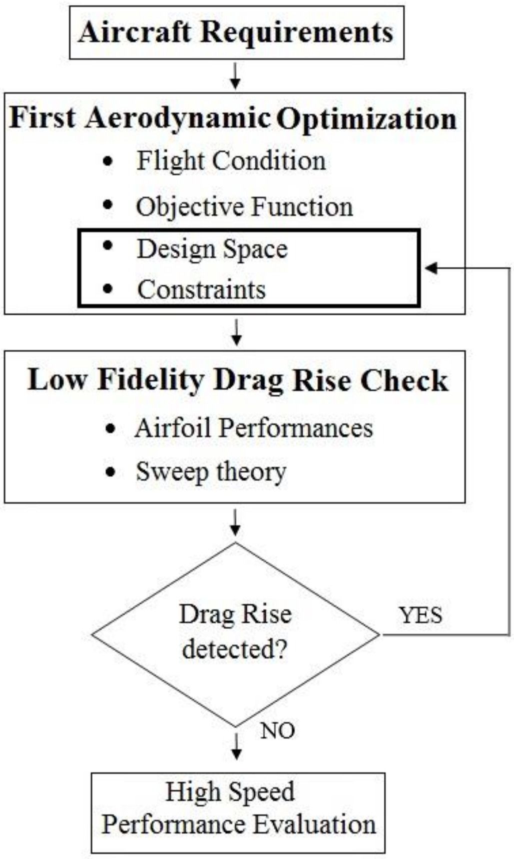


Figure 5: Low fidelity calibration procedure

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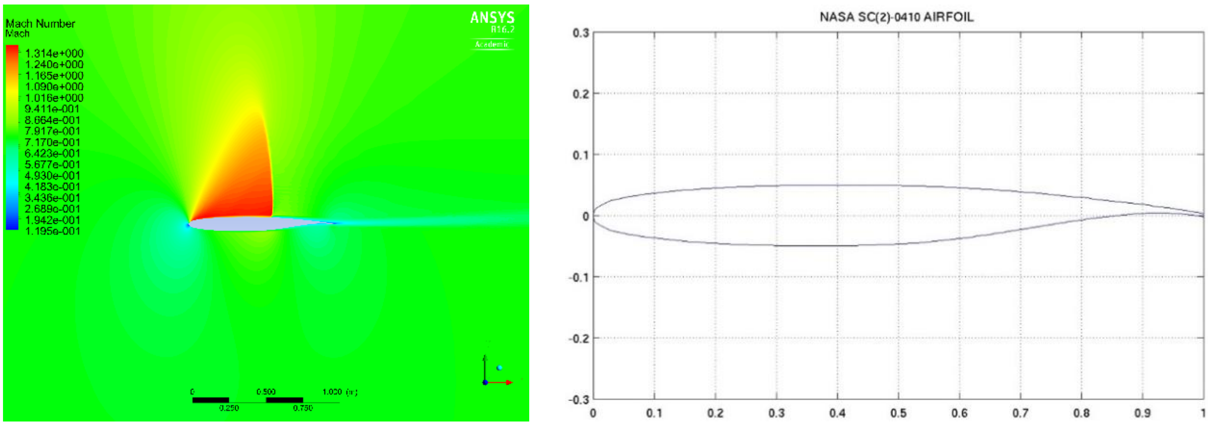
First of all, a group of supercritical airfoils has been chosen and a performance database has been created; the aerodynamic characteristics of the airfoils have been assessed by means of two dimensional CFD analyses, varying Mach number, thickness-to-chord ratio and lift coefficient. Figure 8 shows an example of a two-dimensional CFD analysis in the case of a transonic airfoil.

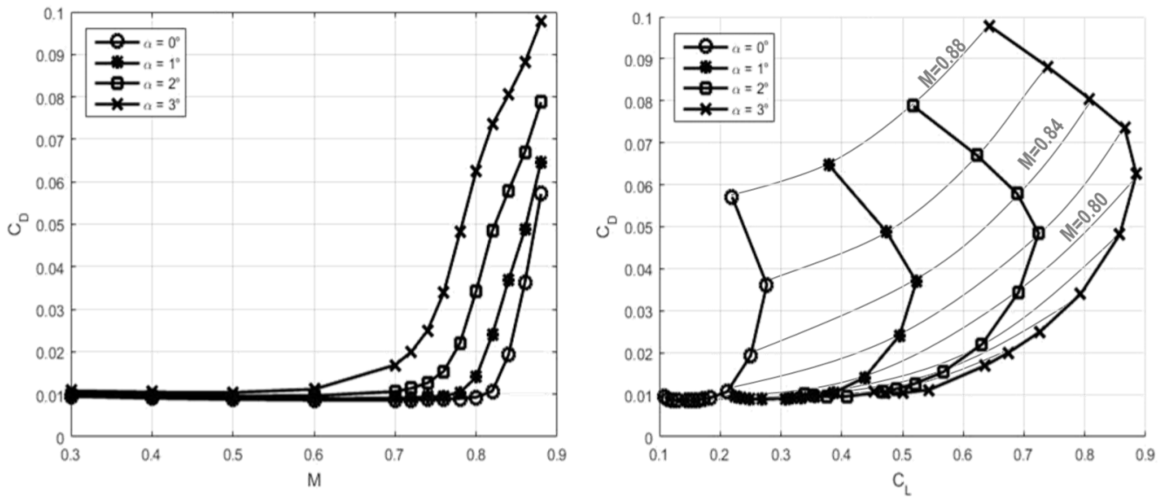



(a) (b)

Figure 6: Generic Mach contour plot (CFD analysis, $\alpha = 3°, M = 0.76$) for the NASA SC20410 airfoil (a) and airfoil sketch (b)

Figure 7 shows the characteristics of the NASA SC20410 profile: Figure 7-a shows the $C_D$ vs M curve and it is apparent how the angle of attack (or $C_L$) influences the drag rise and how $C_D$ is constant at subsonic Mach; Figure 7-b is the polar curve and, again, the importance of the transonic effect increases, especially at high angles of attack.

In particular, the curves (at fixed incidence) show an increment of $C_L$ and a larger increment of $C_D$ due to the compressibility effect; as is well known, the reduction of $C_L$ due the shock stall phenomenon, occurs at lower Mach number at higher angles of attach or, in other words, the airfoils are efficient inside of a limited incidence interval. These results are taken into account in the adopted optimization procedure; the main consequence is the introduction of the sweep angles of the wings and additional constraints on twist angle of wing sections.




(a) (b)

Figure 7: Cd vs Mach number at different angles of attack (a) and Polar Curves (b) for NASA SC20410 airfoil

The lifting surfaces of the configurations obtained with the first optimization process have been divided in a number of strips along the span (excluding the tip and the root zones, where the local, three-dimensional effects influence significantly the aerodynamics); the geometric and aerodynamic properties of the single strips are known, as far as airfoil and thickness; other known data are the $c_l$ distribution along the span, the asymptotic Mach number and the sweep angle of each bay; by means of the simple sweep theory, the actual properties of each section are derived and then compared with the data stored in the supercritical airfoil database.

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In this way, it is possible to identify the lifting surfaces under the drag rise effect (a generic example is shown in Figure 8) and the groups of configurations affected by increases of drag. This low fidelity model in transonic, in a conceptual design stage, is useful to identify preliminarily the influence of the design parameters (both geometric and aerodynamic) on the drag increases. In the example of Figure 8, the marked strips indicate the possibility of the onset of strong shock waves.

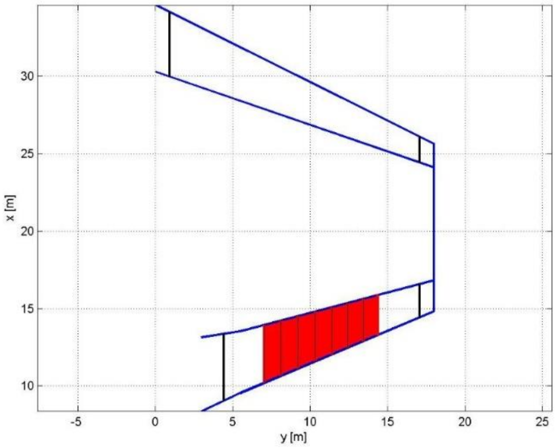


Figure 8: Example of drag rise check on a generic configuration

A new calibration of the lower and upper boundaries of the design space, and also of the constraints, has been made at the end of this procedure in terms of (in this example) maximum local $c_l$, sweep angle, wing loading, etc. Since it is extremely difficult to obtain reliable results related to the transonic range with low fidelity models, a further calibration of the optimization parameters has been carried out by means of high fidelity analyses, with CFD computations (RANS models) on a certain number of reference configurations; a flow chart of the correction procedure is shown in Figure 9.

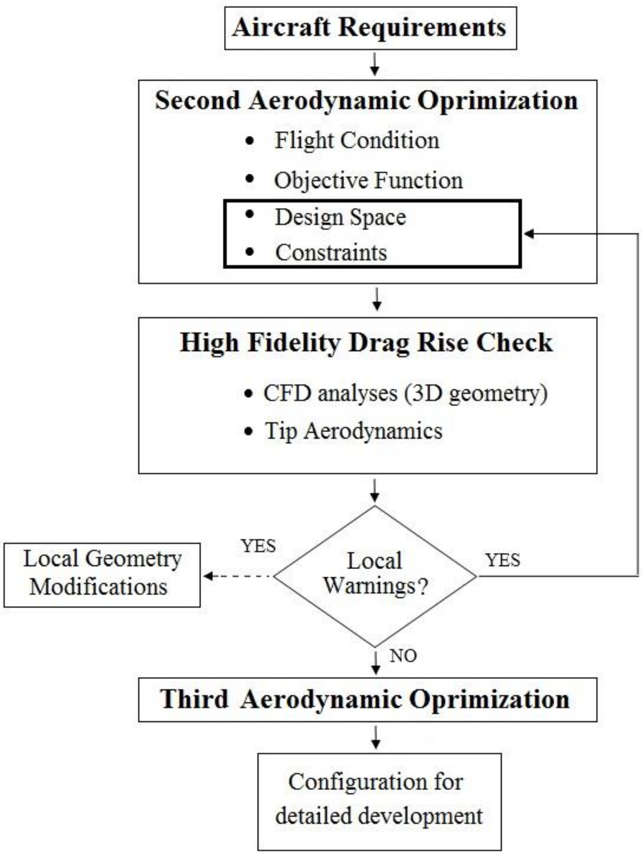


Figure 9: High Fidelity correction procedure

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This second aerodynamic optimization process has been conducted under the inputs originated by the first lower fidelity calibration. Some reference configurations have been chosen in the set of the optimized ones to perform more detailed analyses; in particular, these analyses have been focused on the aerodynamic behaviour of the tip zones where three-dimensional effects due to the influence of horizontal and vertical wings are present. Figure 10 is a typical example of the presence of shock waves originated by different causes, such as: airfoil thickness, local twist angle of the wing, geometrical effects, mutual influence of the vertical and horizontal wings. Starting from these results, the constraints and the boundaries of the vector of the optimization parameters have been calibrated, for a third more refined aerodynamic optimization.

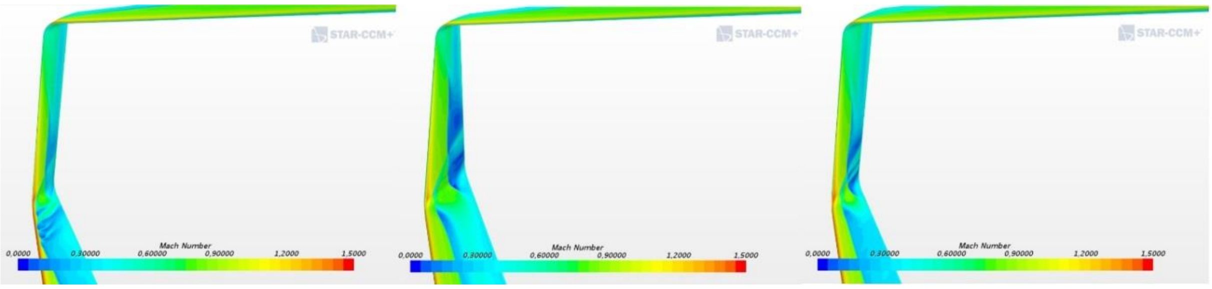


Figure 10: An example CFD result and local geometry modification

In the case of the transonic aircraft considered for PARSIFAL project, the wing loading to be adopted depends also on the transonic characteristics, on the low speed controllability and, according to the design range, on the fuel to be embarked into the internal volume of wings. The CFD analyses allowed us to modify the tip twist and chord and to avoid the detrimental shock-induced separation in the boundary layer (i.e. in the first image of Figure 10), meanwhile maintaining the same total lift on the wing. These indications have been also inserted in the loop, to correct the input parameters of the whole procedure. CFD calculations shown before have been performed on a half-model made of 110 million of cells, using the software STAR CCM+ and the computing facilities of University of Pisa.

Figure 11 shows some typical results obtained after modifications of the front wing tip of a generic configuration. Each symbol corresponds to a local minimum; all the families relevant to different wing loadings contain a set of configurations which satisfy the constraints (e.g.: trim, stability of flight) and the boundaries of the design vector and, also, minimizes locally the drag coefficient. Figure 11 shows what is well known, namely that the higher wing loading solutions are most efficient in the subsonic range.

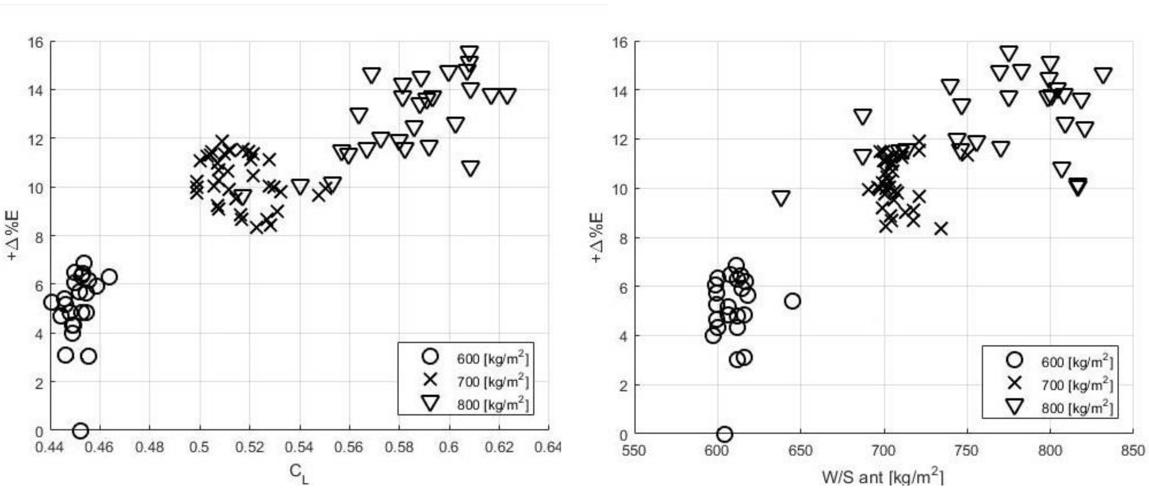


Figure 11: Efficiency results for some generic groups of configurations

At the end of these procedures, some configurations have been chosen for further detailed analyses, in order to focus on the best design ranges in term of wing loading and drag minimization, taking the presence of local aerodynamic effects into account. Figure 12 reports the planforms of four configurations having the front wing loading equal to *500*, *600*, *700* e *800* $\mathrm{kg/m^2}$, respectively; they will be used as test case for the further analyses.

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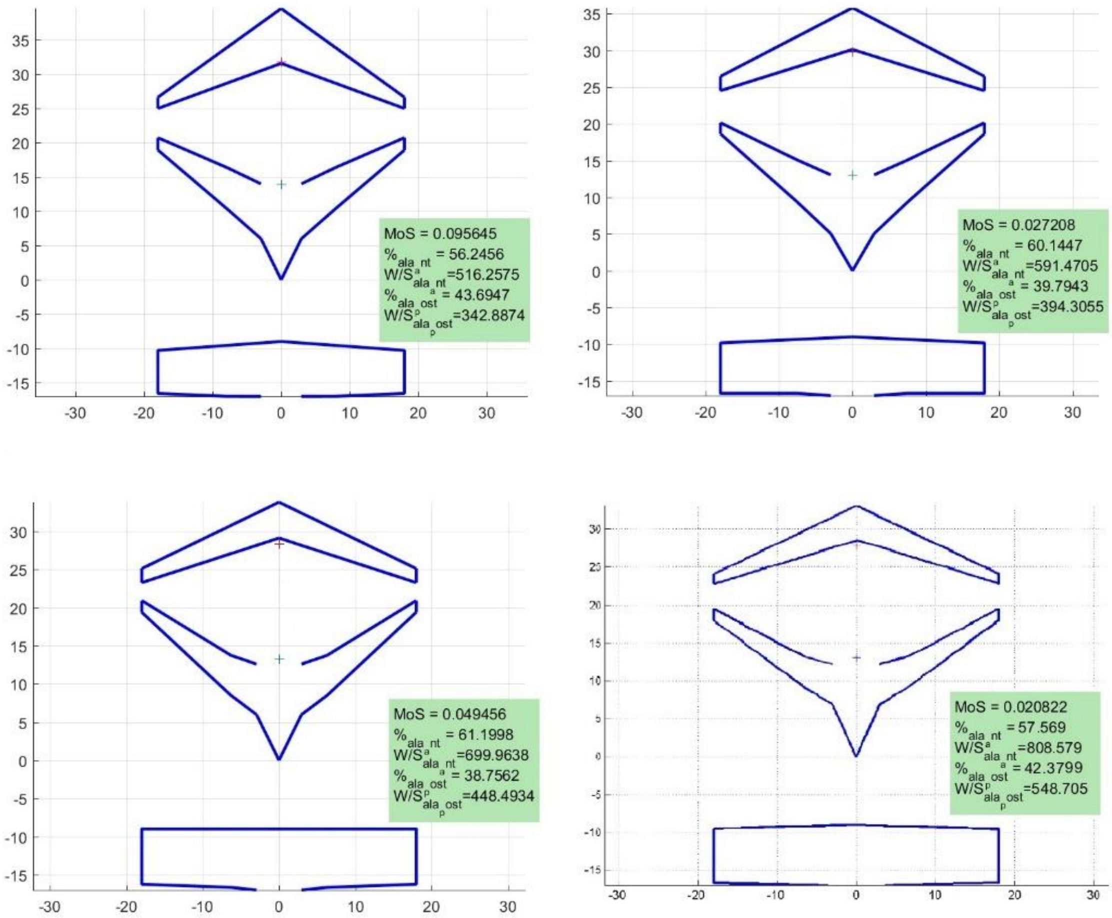


Figure 12: Four configuration with different wing loading

The symbols in Figure 12 indicate the margin of stability (MoS), the percentage of lift on the front and rear wings (% ala ant and % ala post, respectively), the wing loading on the front and rear wing W/S. It can be remarked that the constraint on the wing loading is respected by the front wing; the rear wing loading results as a consequence of the optimization and, in particular, is lower than the first one.

# 4 Conceptual sizing procedure for high-lift devices and control surfaces

The PrandtlPlane configuration allows to choose several different solutions for the positioning of control surfaces on both wings; in this stage of the design, a first sizing of control surfaces and high lift system has been performed according to the following guidelines:

- the elevators are placed at the root region of each lifting surface;
- the ailerons are installed on the tip of both wings,
- the remaining space in wing-span is reserved to trailing edge high lift devices.

The elevators are counter-rotating, ideally generating a pure moment: in this way, the pitch control effectiveness is improved and the variation of vertical force due to elevators deflection is minimized. This solution increases the safety of flight, as, for example, in the event of a low altitude pull up maneuver (landing aborted). Figure 13 shows a sketch of this layout.

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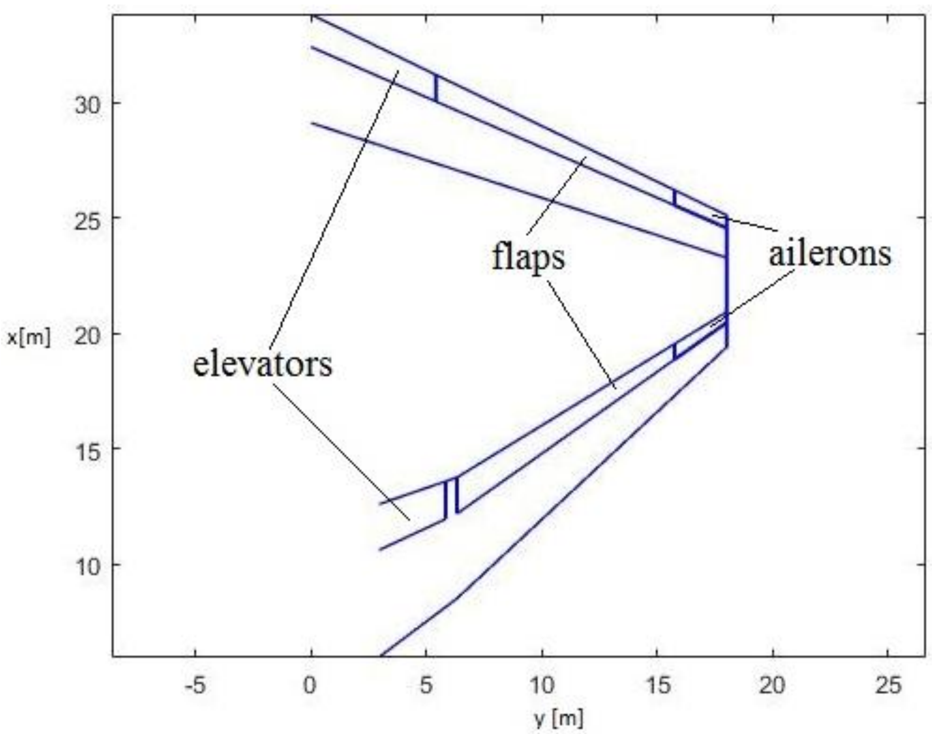


Figure 13: General layout of control and high lift devices surfaces

A preliminary sizing procedure for both elevators and flaps has been defined in approach condition; the procedure is initialized with a first sizing of the ailerons (based on statistical data of jet-liners), in order to identify the available span in which flaps and elevators can be allocated. Once the conceptual layout for the control surface system has been established, including a first sizing of the elevators and the flaps, it is possible to evaluate the performance of the lifting system with the high lift devices activated, by means of an approximated procedure ([9]) which provided an estimation of $C_{Lmax}$ . Then, it is possible to solve the low speed trim problem, defined as follows with the conventional meaning of the symbols:

$$\begin{cases} C_L = C_{L\alpha}\alpha + C_{L\delta e}\,\delta_e + C_{L\delta f}\,\delta_f \\ 0 = C_{m0} + C_{m\alpha}\alpha + C_{m\delta e}\,\delta_e + C_{m\delta f}\,\delta_f \end{cases}$$

The trim problem is solved by using the AVL code; in particular, once flap deflection is provided as an input, the elevators deflection ($\delta_{e\,trim}$) and the angle of attack ($\alpha_{trim}$) are calculated by the solver in order to fulfil pitch moment equilibrium and the condition $C_L = C_{L\,approach}$.

The flight condition is defined as follows:

- h = 0 m, SL flight altitude
- W = MLW, Maximum Landing Weight
- $V = V_{approach} = 1.3V_{stall}$

The procedure of trim solving and elevators and flaps sizing is iterative, since the elevator deflection cannot exceed a threshold (from statistical reference values). If this constraint is not satisfied, the span of the elevator is increased until its deflection is inside the fixed range. Obviously, the increase of the elevator span causes a decrease of flap span, with a consequent variation of the flapped lifting system's performance. The design procedure is schematically reproduced in Figure 14.

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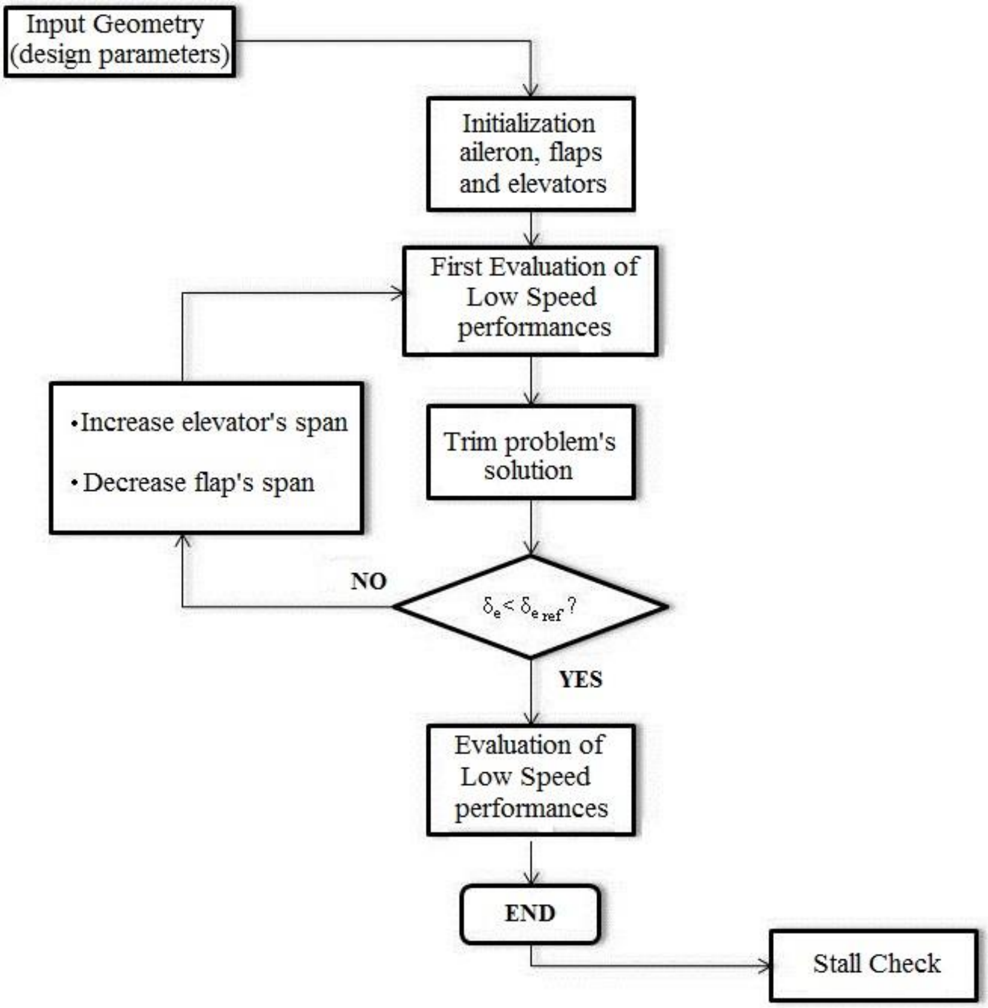


Figure 14: Preliminary sizing procedure

Starting from an initial configuration, several different solutions are obtained in terms of span and deflections of flaps and elevators, and also in terms of global low speed performances. As an example, setting N different flap deflections for the front wing, and, for each of them, M deflections for the rear wing flaps, the resulting NxM different combinations can be evaluated, in order to find the best trade-off between the trim requirements and the performances. The last step of the process is a preliminary check of stall on each configuration calculated; the check is done by comparing the calculated $c_l$ span distribution with the $c_{l\,max}$ of the flapped airfoil.

The results obtained by this procedure represent a first guideline for the following detailed design, and they provide some interesting preliminary indications on the performances and the influence on these of the principal design parameters, like the wing loading, the maximum landing weight, the shapes of the lifting system and flaps.

## 5 Conclusions

The main characteristics of the PrandtlPlane configuration are briefly discussed in the paper. The box wing concept allows to design a lifting system with minimum induced drag among all the possible solutions. In order to maximize the global efficiency, the friction drag and, in the transonic range, the wave drag must be reduced. The preliminary aerodynamic design of a PrandtlPlane has been carried out with a given span of 36 m, typical of the most common civil aircraft as A320 and B737, but with the capacity of about 320 passengers, typical of the upper category aircraft. A new fuselage concept has been introduced with a larger horizontal dimension, two aisles and the presence of central struts against pressurization loads. The design of the lifting system is conducted according to a mixed procedure, making use of subsonic optimization followed by high fidelity CFD analyses.

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