



The importance of coupling aerodynamic and cost analysis in aircraft design

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Abstract

Companies are increasingly required to improve their quality, flexibility and innovation while maintaining or reducing their costs. However, engineering and finance are often handled by different staff groups at different times in the manufacturing process, and by uncoupling engineering and finance, a company runs the risk of overlooking important interactions between the two. A design system that performs engineering and financial analysis simultaneously may, therefore, improve upon the efficiency and effectiveness of the traditional methods, as the existing practice of designing aircraft from a technical perspective without simultaneously considering the impact on overall program value is not optimal in a business sense. A coupled performance/financial framework enables an integrated approach to technical design and programmatic decisions. This work thus seeks to couple aero performance and financial design. Specifically, a multi-objective trade study is conducted to see the impact on the direct operating cost (DOC) and manufacturing cost of parametrically varying aircraft wing thickness to chord ratio along the wing span. While the present process is only partially automated, the purpose is to establish a useful foundation for further developments and to gain insight into the interactions between technical and program design.

Keywords Aerodynamics · MDO · Cost modelling · CFD · Design integration

Abbreviations

AFW	Airframe weight
CFD	Computational fluid dynamics
DOC	Direct operating cost
FEM	Finite element method
IRR	Internal rate of return
MDO	Multi-disciplinary optimisation
NRC	Non-recurring-cost
RANS	Reynolds averaged Navier Stokes equations
RC	Recurring cost
SFC	Specific fuel consumption
TAU	Triangular, adaptive and unstructured

1 Introduction

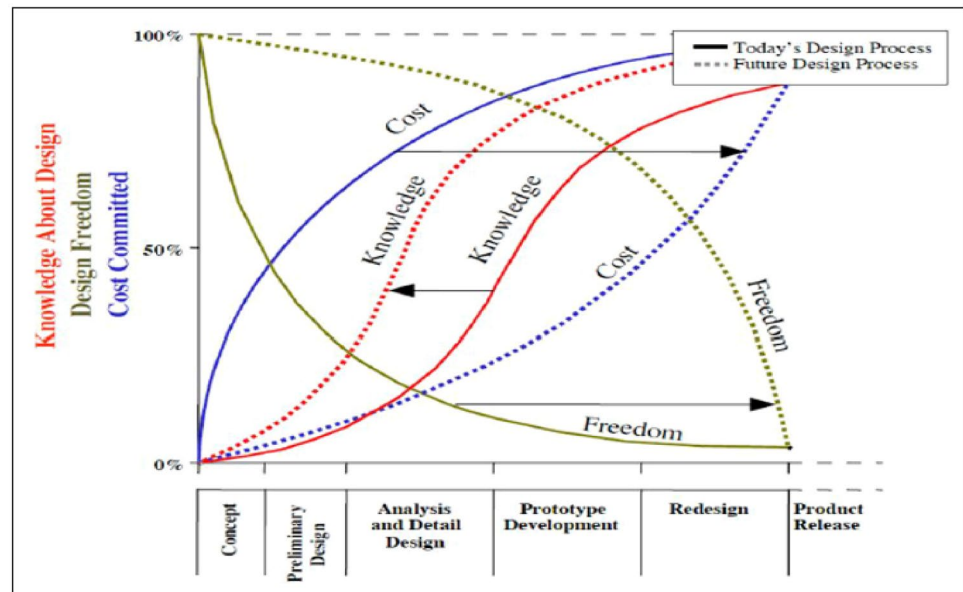
Cost is a factor of success in the product/service of many industries. Reducing cost is of great importance for survival in today competitive market. Costs are becoming an important factor and aerospace companies are looking forward to reduce the cost without compromising on performance. The environmental impact of the aircraft's life cycle is increasingly impacting its development. Thus, future design choices will also have to take into account manufacturing and operating constraints which may result in additional costs (new certification standards, fuel or journey taxes for operators, recycling costs for materials and end-of-life aircraft, etc.). Aircraft producers are now more aware than in the past, that the demand to reduce cost and lead-time needs to be tackled at the conceptual and preliminary engineering design phase. Typically, 65–80% of the total avoidable cost is controllable at the early design stage and certainly many engineers concur that conceptual and early design phase hold the greatest cost influence [1], see Fig. 1. Although the design process accounts for only 10% of the product cost, it indirectly have an effect on the final cost up to 80%, well before the real product costs happen [2]. Indeed, conceptual design stage is the phase where downstream cost associated with bad design

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Fig. 1 The overall aircraft design development process phases related to product life-cycle cost, design knowledge and freedom [5]



is often embedded. Hence, it is important that all the factors, which contribute to the total cost of the product, are considered earlier in the design phase [3].

It is claimed that the accuracy of a cost estimate improves with the volume of information available. Cost estimation is a process that provides progressively more accurate information as a project moves from conceptual through final design and construction award. But, the cost of a product is not known in advance of production and a cost estimation method is essential. As the design cycle continues, the project collects worker hours of design activity. This implies that it is progressively hard to prematurely end, whether a later cost estimation on the itemised plan shows an over-spending condition [4]. Even during these later stages of design, designers typically optimise the functionality and then determine what the cost is rather than doing a full optimisation including costs. If, after the detailed design phase, designs are discovered to be excessively costly, usually the action that many companies take is to try to decrease costs by such procedures as changes in assembling and the utilisation of different materials, instead of re-planning out the avoidable expenses. The probable outcome of this arrangement is normally a decrease in both expense and quality [4]. Therefore, a wrong decision at this stage is extremely costly further down the development process. Production modifications and process alterations are more expensive the later they occur in the development cycle. As a consequence, a more mindful methodology to the issue of cost is necessary. In aerospace engineering, there has always been a wide variety of manufacturing alternatives, whether processes, methodologies, or technologies, there are even more materials now available. Data management systems are continually evolving, and improving in computational

modelling is being pursued on all fronts, although especially in computational fluid dynamics (CFD) and finite element modelling (FEM) for aerospace applications. In any case, there is as yet a fundamental need for cost tools that support and back engineers in settling on sensible and estimated plan choices that are financially savvy and at last, more competitive [6]. While multidisciplinary analysis and optimisation has seen extensive use for technical design problems in aerospace, there has been less emphasis on applying these techniques to larger scope system design. Aerospace manufacturers today are searching for techniques to gain a sustainable, competitive advantage in the global marketplace. In the past, technology was the main driver in the aircraft design process. Nowadays, there is a demand of cost reduction in the commercial aircraft industry to satisfy customers' needs. In recent years, there has been growing emphasis on the need to provide transparency in the costs of engineering programs, leading to growing emphasis on whole-life cost modelling techniques. This has arisen largely due to the increased interest in longer timescale projects and programs [7]. The main challenges faced by Airlines is to keep low the operating cost, providing high level of service, higher frequency of flights to destinations and cheap air fares. Airline companies have to do lots of activities like cutting the cost of maintenance of their fleets and increasing the dispatch reliability to stay and make money from the business. All this depends upon how the aircrafts are designed. A better design approach also takes into account factors such as development and manufacturing costs. Integrating data and knowledge created from manufacturing activities into the design process has been the subject of research in knowledge management and related disciplines. These initiatives focused on ways to improve technical requirements and

supplier decision-making to improve manufacturing quality by minimizing faults [8]. However, infrequently previous research has dealt with the integration aspect as part of a centrally driven systematic workflow that enables collaborative knowledge capture between the internal design teams and manufacturing engineering teams. This aspect had already been identified by many researchers to be under-addressed and a very significant challenge of collaborative within the research related to improving collaboration in the design process for the aerospace industry remains still limited [9]. Even less research has been devoted specifically in coupling aero and manufacturing engineering domains.

2 Cost in aircraft design

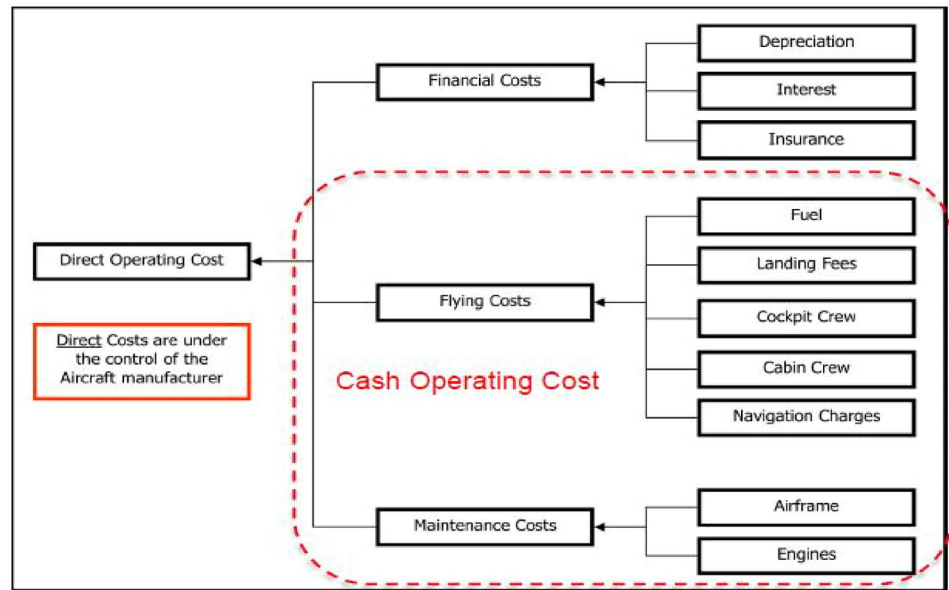
The importance of engineering costing within aircraft design should have a more directly influential role. A challenge for the scientific community is to adapt and to exploit the trend towards greater multidisciplinary focus in research and technology, particularly with regard to utilizing cost as a metric within the process. The final aim is that aircraft design has to be driven by a well-balanced trade-off between performance and cost that leads to an affordable and suitable product life cycle for the operators. Curran et al. [6] gives a different classification of estimating approaches for the aerospace industry, saying that there is no consolidating theoretical approach for cost engineering. More information about cost engineering techniques and the state of art costing tools can be found in [10, 11] where Roy conducted an interesting review of existing methods. Most of the current cost models focus on a particular manufacturing process or a specific maintenance aspect, therefore, not providing the whole picture. The main challenge in modelling the manufacturing cost, associated to a new aircraft at the initial design stage, is to examine all the cost features and the way to link them into the decision making process. It is important to understand the cost related to different competing designs, and this can be tackled by including cost estimation in the design process. Estimating the cost at the early design stage is paramount to reduce the life cycle cost of the aircraft. A new methodology for the generation of a cost estimation approach for preliminary aircraft design in a multidisciplinary environment has been presented by the author in a previous paper [12], which is built in Excel using a visual basic interface and it is integrated within an integration/process building environment framework (Model Center-Phoenix Integration). It can be treated as a component of a larger computational design process. In addition, in the cited paper, a detailed explanation of the different cost categories acknowledged as being sustained by an aircraft manufacturer, including the main cost requirements that should be included into a multidisciplinary design process to achieve an economic and efficient

aircraft, together with an overview of different cost modeling approaches currently used in aircraft industry.

3 Aero cost trade study

While multidisciplinary analysis and optimisation has seen extensive use for technical design problems in aerospace, there has been less emphasis on applying these techniques to larger scope system design. Engineering and finance are often taken care of by various groups and at different times. By uncoupling engineering and finance, an organization risks ignoring significant interactions between the two. A design methodology that accomplish engineering and financial analysis concurrently could enhance the efficiency and functionality of the conventional methods [13]. Traditional commercial aircraft design attempts to improve performance and reduce operating costs by minimizing take-off weight. Notwithstanding, such a methodology does not ensure the profitability of a given airplane design from the point of view of the airframe maker [13]. A better design approach also takes into account factors such as development and manufacturing costs. In an increasingly competitive market for commercial aircraft, manufacturers may wish to design for improved financial viability of an aircraft program in addition to technical merit before undertaking such a costly investment. The current practice of designing aircraft from a technical perspective without at the same time considering the impact on the overall program value is not ideal in a business sense. The coupled performance/financial framework enables an integrated approach to technical design and programmatic decisions. The objective of this work is to couple aero performance and financial design. Specifically, a trade study is conducted to see the impact on the direct operating cost (DOC) and manufacturing cost varying parametrically the wing thickness to chord ratio along the wing span. The costs of flying operations, as well as the maintenance and depreciation of the flying material, are generally referred to as direct operating costs. In spite of the fact that the DOC constitutes only one aspect of an airliner's economic profitability, it receives the most attention because several factors that contribute to the DOC are directly related to the airplane's technical design and operational attributes, and thus are partially under the design team's control [14]. The breakdown of the direct operating cost is shown in Fig. 2. The direct operating cost consists of financial, flying and the maintenance cost. The Financial cost is further decomposed to depreciation, insurance and interest whereas maintenance cost is decomposed to airframe and engine maintenance. Fuel, landing fees, cockpit crew, cabin crew, and navigation charges are all included in the flying cost. Crew expenditures make up a significant portion of the DOC, but they are out of the designer's control. Fuel is inextricably tied to aircraft

Fig. 2 Schematic of the direct operating cost

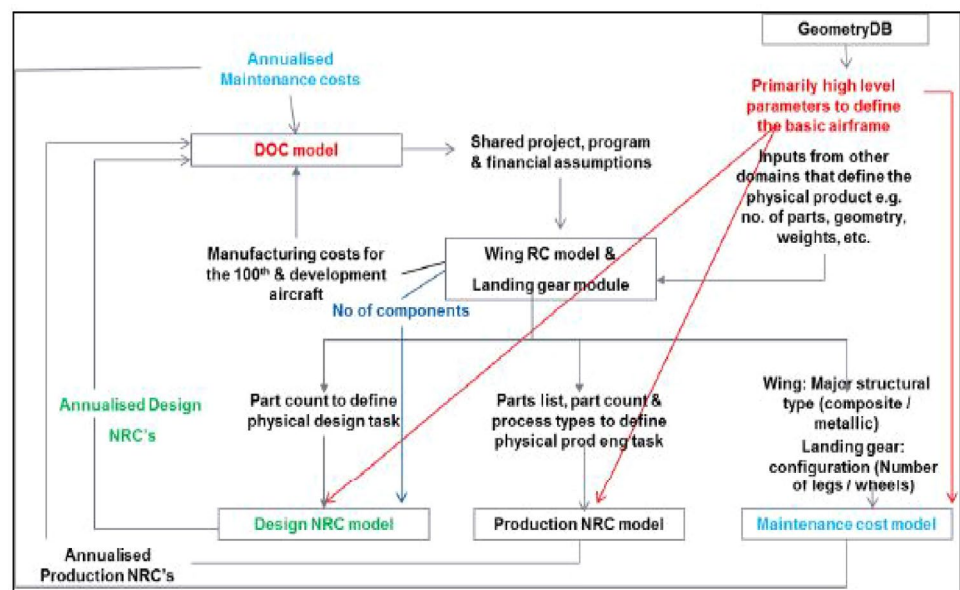


engine performance and aerodynamic characteristics, as well as to fuel price, which varies greatly depending on time and location. Maintenance costs are an essential portion of the aircraft life cycle cost, which can be five times the cost of acquisition and accounts for 10–20% of direct operating costs, forcing both aircraft makers and operators to keep them under control. The depreciation, insurance and interest are financially orientated and are then in the cost model generated from the total aircraft price, which is based on the aircraft production cost. The production cost is the summation of the part manufacturing and connection assembly process cost. Both of them include material cost and labour cost. For assembly process, materials refer to additional

parts or miscellaneous such as fasteners. The element of crew, fees, and maintenance cost are operating oriented and are consequentially evaluated based on the airframe weight (AFW). More details of the cost suite, input required and output produced and how been calculated can be found in a previous paper published by the author in 2019 [12]. In Fig. 3, a schematic of the data flow structure for the DOC calculation is shown.

In a nutshell, the cost model developed and applied in this analysis is capable of capturing the features of a design that drive the manufacturing cost, which are typically not only weight but also the aircraft’s physical geometry. This enables the assembly and detailed manufacturing costs, to

Fig. 3 DOC data flow



be established by means of a relatively detailed component layout using Knowledge Based manufacturing rules. In addition, the parameters from one area have an impact on other areas, for instance, the configuration of the aircraft has a direct influence on the required design and production engineering effort, as well as the costs required for tooling. The cost model suite also considers the impact of a design on the operational cost (particularly maintenance) by considering the major features of the design generated as part of this process. Furthermore, the mass of different wing components, such as front and rear spar, ribs, stingers, and skin can be an input, conversely if not information has been given the mass is calculated by the cost tool automatically, using volume and material density and number of components, extracting geometric features from the 3D CAD model of the wing structure. Indeed, the minimum requirement for the cost model to run is the High Level geometrical description, among which thickness to chord ratio is one of this

parameter. While the process is not fully automated, the purpose is to establish a useful foundation for further study and to gain insight into the interactions between technical and program design. In fact integrating aero/structural coupling at the same time for better overall efficiency is a key factor.

4 Use case problem formulation

The test case under investigation is a conventional single aisle commercial aircraft, which is representative of an A320-like aircraft, as in Fig. 4, to generate realistic aerodynamic performance through modifications to the camber and thickness distributions of the wing.

Thickness-to-chord-ratio is a key measure of the performance of a wing when it is operating at transonic speeds. Moreover, a slight modification of this parameter has an impact on the wing box structure that in turn affects its manufacturing's cost. Starting from the reference geometry, ten new wings with different thickness over chord, t/c , have been generated. Specifically, the thickness over chord along the span has been reduced from the baseline wing respectively of 3%, 5%, 7%, 10% and 12% as can be seen in Fig. 5.

The t/c has been modified in two ways. First, the upper surface has kept constant and the thickness modified moving only the lower surface, see Fig. 6.

Afterwards the thickness has been modified moving both surfaces, keeping constant the camber, see Fig. 7.

The aerodynamic parameters for the aircraft are calculated using TAU (triangular, adaptive and unstructured), RANS code developed by DLR. In the design of transonic wings, it is particularly important to use high-fidelity models to correctly predict the drag due to viscous and compressibility effects. For this, an unstructured mesh has been

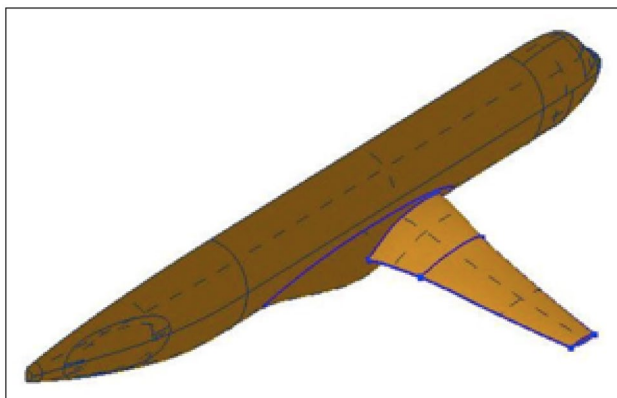
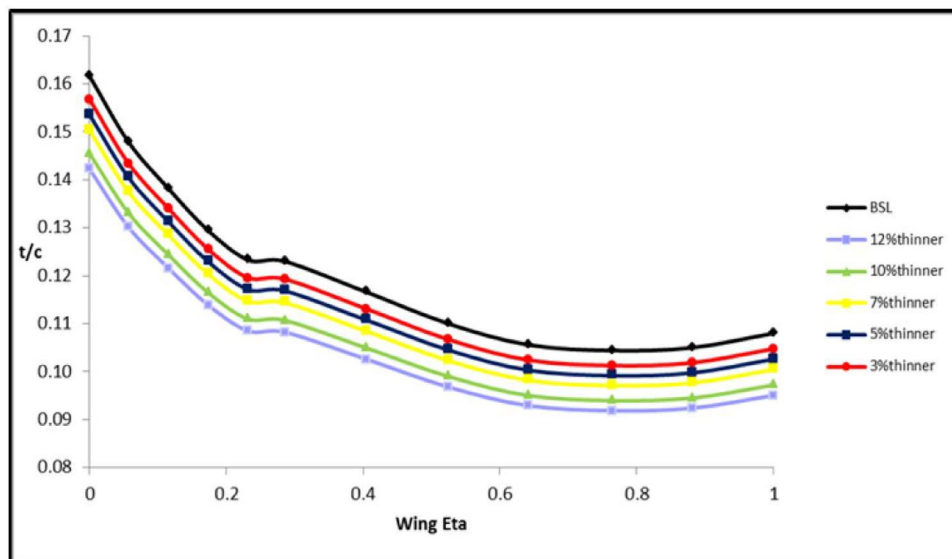


Fig. 4 Test case, single aisle mid-range commercial aircraft

Fig. 5 Thickness over chord variation along the span



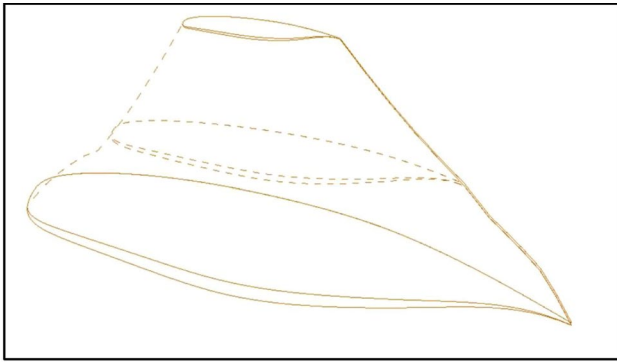


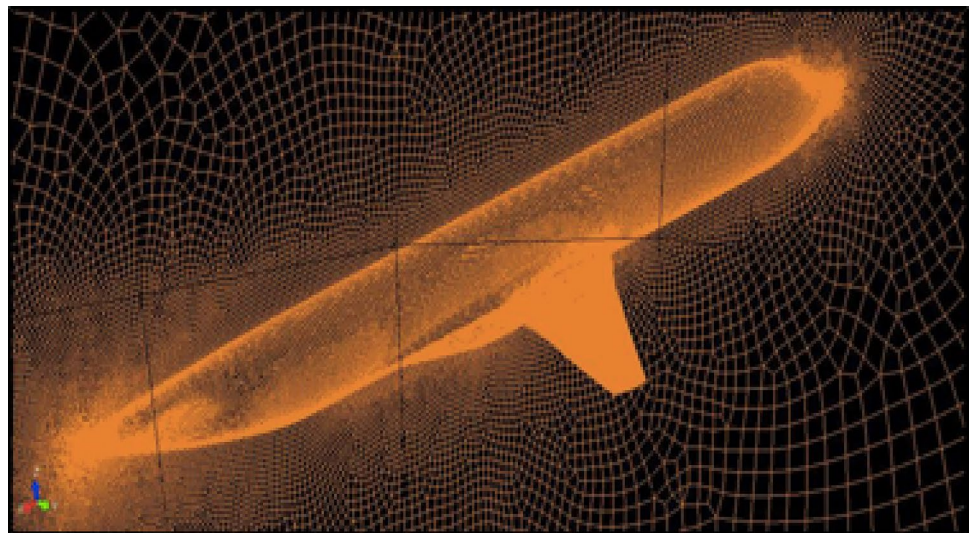
Fig. 6 Example of t/c modified moving only the lower surface



Fig. 7 Example of t/c modified moving both surfaces

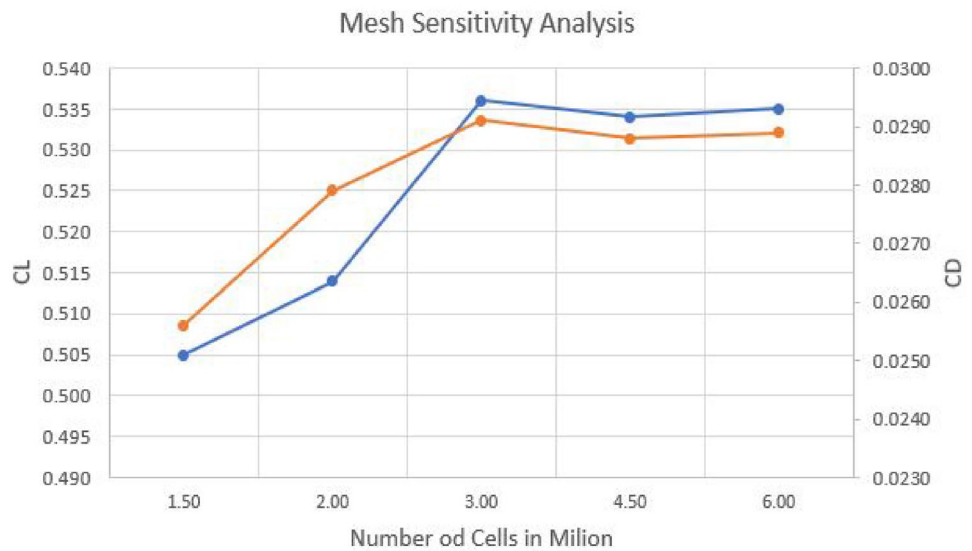
generated, for which the surface mesh is made up mainly of quad elements. The mesh is shown in Fig. 8. It is made up of nearly 3 million cells, and the far-field boundary is a semi hemisphere with a radius of 20 times the wing root chord.

Fig. 8 Unstructured mesh around the aircraft



The grid independence analysis has been performed for the Baseline case at cruise speed of Mach 0.8 and an angle of attack = 2 degree, which is the nominal cruise angle, detail of which can be seen in Fig. 9. The cruise phase is the longest mission phase of a civil airliner in which more of the fuel is consumed and the fuel cost is one of the main components of the direct operating cost. A pressure far-field boundary condition has been applied to the external domain and a no-slip condition at the aircraft surface.

In the aircraft's boundary layer, the flow gradients are extremely "anisotropic". The gradients normal to the surface through the boundary layer have a very high flow gradient whereas by comparison the flow gradients along the surface are relatively small. The mesh needs to reflect this and this is the reason for the creation of a "near-field" mesh. The majorities of cells in the near-field mesh are very close to the surface and are composed of thin flat hexahedra to have a good resolution of the boundary layer. The RANS CFD solutions have been run, in the cruise phase of the mission in which an aircraft spends much of its flight time, for all the eleven cases from the angle attack range between 0.5 and 4 degrees at cruise speed of $M = 0.8$ at an altitude of 36,000 feet. The analysis is completed when the lift and drag coefficients have achieved the required degree of convergence. The integral aerodynamics coefficients are extracted at cruise condition. The ratios L/D have been used to calculate the required fuel for the longest flight mission allowable for this aircraft. Since aircraft fuel economy is directly impacted by technology advancement, examining the relationship between fuel consumption and DOC provides a valuable insight into understanding the influence of aircraft aerodynamic performance improvement on aircraft cost. The results in term of integral parameters for the baseline and for all cases for which the t/c has been modified moving both

Fig. 9 C_L and C_D values from the mesh sensitivity analysis

surfaces, that from now on for simplicity will be indicated as “both” cases are reported in Table 1.

The lift and drag polars and the relative deltas are reported respectively in Figs. 10 and 11. Neither the magnitude nor slope of lift curve change, but there is an increase in the achievable maximum lift. The total drag has been decomposed in its components using a Drag breakdown tool, which make use of a far-field analysis, and the results reported in term of viscous, induced and wave drag, respectively, in Figs. 12, 13 and 14.

The drag breakdown shows that the viscous drag and the lift-induced drag constitute the two main sources of drag as expected for a civil transport aircraft, where the lift-induced drag is approximately one third of the total drag. The overall trends suggest reducing thickness leads to an associated reduction in viscous drag. Thickness reductions have little effect over majority of C_L range in term of induced drag. Reducing thickness leads to reduce wave drag over all C_L values. The results in term of integral parameters for the baseline and for all cases for which the t/c has been modified moving only the low surface that from now on for simplicity will be indicated as “low” cases are reported in Table 2.

The lift and drag polars and the relative deltas are reported, respectively, in Figs. 15 and 16.

Moving the low surface leads to camber change (increases as thickness decreases). Hence, this explains why lift curves are shifted. As in the previous both cases, the total drag has been decomposed in its components using the same Drag breakdown tool, and the results reported in term of viscous, induced and wave drag, respectively in Figs. 17, 18 and 19.

In all cases is found that the lift-induced drag does not vary too much with the thickness variation. This is fairly expected given that lift-induced drag is mainly driven by the planform shape, which has not been modified for all

cases under investigation. For the “low” cases, the effect on the wave drag is now quite different—does not really reduce wave drag (as expected since wave drag is mainly influenced by the upper surface shocks, upper surface that has been kept the same), but does demonstrate a delay in rapid drag rise. The required fuel for the flight mission is calculated using the method presented by Roskam [15], and represent. In this method, the required fuel for the cruise is calculated using the Breguet range Eq. 1, where engine, aerodynamic, and structural technologies are represented by three parameters, specific fuel consumption, lift-to-drag ratio, and structural weight, respectively.

$$\text{Range} = \frac{V \left(\frac{L}{D} \right)}{g \times \text{SFC}} \ln \left(1 + \frac{W_{\text{fuel}}}{W_{\text{PL}} + W_0} \right) \quad (1)$$

where W_{fuel} is the carried fuel weight W_{PL} is the payload weight and W_0 is the aircraft empty weight. This simplification might lead to inaccurate prediction of the total aircraft fuel consumption. But in this study, it is not in any way intended to be exact, but rather to give an order of magnitude, thus some rough assumptions are made. The key assumptions are that specific fuel consumption (SFC), L/D , and flight speed, V are constant, and therefore take-off, climb, and descend portions of flights are not well modelled. This assumption in turn leads to inaccurate calculation of fuel burn, mission range and time, and thus an inaccurate DOC. Moreover, most fuel burn computation focuses more on the cruise portion, which is critical for range missions for commercial aircraft. The analysis exclusively examined the cruise phase of flight, ignoring the climb and descent even because fuel spent on non-cruise flight segments such as take-off and landing is a much smaller fraction of the total

Table 1 Aerodynamic coefficients and the ratio L/D for the baseline and all “both” cases

Alpha	Baseline			3% both			5% both		
	Cl	Cd	L/D	Cl	Cd	L/D	Cl	Cd	L/D
0.50	0.369	0.021	17.736	0.370	0.021	17.899	0.368	0.021	18.007
0.75	0.402	0.022	18.254	0.402	0.022	18.456	0.400	0.022	18.559
1.00	0.433	0.023	18.328	0.434	0.023	18.850	0.432	0.023	18.966
1.25	0.465	0.025	18.878	0.466	0.024	19.119	0.464	0.024	19.241
1.50	0.497	0.026	19.004	0.498	0.026	19.263	0.496	0.025	19.388
1.75	0.530	0.028	19.003	0.531	0.027	19.282	0.528	0.027	19.411
2.00	0.536	0.029	18.785	0.564	0.029	19.084	0.562	0.029	19.221
2.25	0.595	0.032	18.350	0.597	0.032	18.662	0.594	0.032	18.809
2.50	0.620	0.035	17.745	0.629	0.035	18.054	0.626	0.034	18.216
2.75	0.655	0.038	17.024	0.659	0.038	17.322	0.657	0.037	17.498
3.00	0.681	0.042	16.234	0.688	0.042	16.515	0.685	0.041	16.709
3.25	0.701	0.045	15.400	0.711	0.045	15.663	0.709	0.045	15.882
3.50	0.715	0.049	14.544	0.726	0.049	14.784	0.727	0.048	15.033
3.75	0.724	0.053	13.712	0.737	0.053	13.923	0.739	0.052	14.183
4.00	0.730	0.056	12.918	0.744	0.057	13.105	0.747	0.056	13.374
Alpha	7% both			10% both			12% both		
	Cl	Cd	L/D	Cl	Cd	L/D	Cl	Cd	L/D
0.50	0.370	0.020	18.134	0.372	0.020	18.283	0.372	0.020	18.318
0.75	0.402	0.021	18.693	0.403	0.021	18.840	0.403	0.02	18.903
1.00	0.433	0.023	19.099	0.435	0.023	19.247	0.434	0.022	19.327
1.25	0.465	0.024	19.378	0.466	0.024	19.524	0.466	0.024	19.613
1.50	0.497	0.025	19.529	0.498	0.025	19.664	0.498	0.025	19.752
1.75	0.531	0.027	19.573	0.531	0.027	19.707	0.531	0.027	19.787
2.00	0.564	0.029	19.413	0.565	0.028	19.572	0.564	0.028	19.661
2.25	0.598	0.031	19.017	0.599	0.031	19.208	0.598	0.031	19.312
2.50	0.632	0.034	18.422	0.633	0.034	18.642	0.632	0.034	18.762
2.75	0.664	0.037	17.689	0.666	0.037	17.928	0.666	0.037	18.061
3.00	0.695	0.041	16.871	0.698	0.041	17.120	0.699	0.041	17.261
3.25	0.721	0.045	16.004	0.727	0.045	16.259	0.729	0.044	16.408
3.50	0.741	0.049	15.105	0.749	0.048	15.365	0.754	0.048	15.522
3.75	0.754	0.053	14.206	0.765	0.053	14.457	0.771	0.053	14.614
4.00	0.762	0.057	13.351	0.775	0.057	13.585	0.781	0.057	13.726

fuel use. A proper adjustment for fuel burned during non-cruise segments on the ground could be made by the ratio of airborne hours to block hours. The fuel burn is afterwards used as input for the cost suite. The fuselage parameters are assumed to be constant. As for the wing the only parameters modified are the t/c at the root, at the crank and at the tip.

5 Financial results

Once calculated the approximated mission fuel burn, the mission and geometry files input for the cost suite have been updated accordingly and cost analysis launched for all cases and the direct operating cost calculated, see Fig. 20. The cost

model developed and applied in this analysis is capable of capturing the features of a design that drive the manufacturing cost, which are typically not only weight but also the aircraft's physical geometry. This enables the assembly and detailed manufacturing costs, to be established by means of a relatively detailed component layout using knowledge-based manufacturing rules. In addition, the parameters from one area have an impact on other areas, for instance, the configuration of the aircraft has a direct influence on the required design and production engineering effort, as well as the costs required for tooling. The model suite also considers the impact of a design on the operational cost (particularly maintenance) by considering the major features of the design generated as part of this process. The recurring

Fig. 10 Lift polar and relative CL delta for the “both” cases

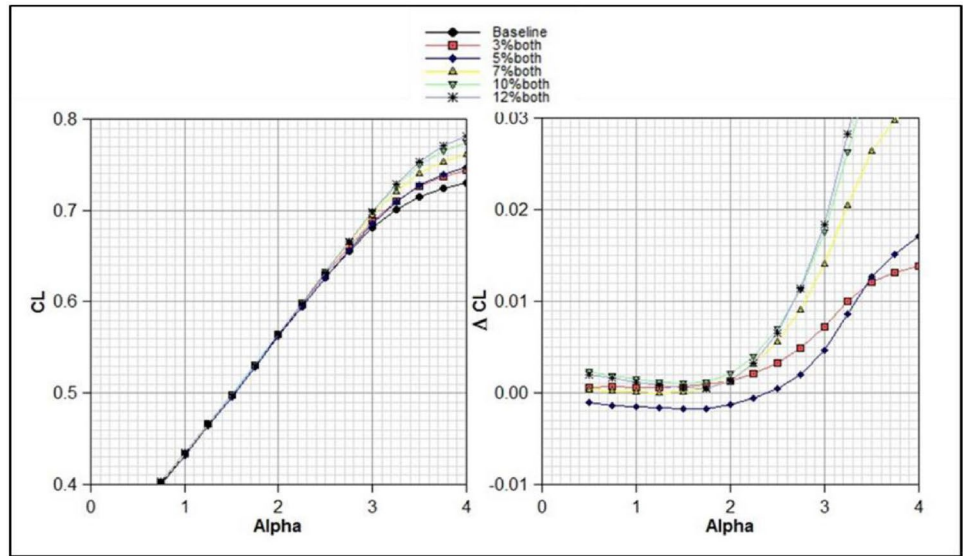


Fig. 11 Drag polar and relative Cd delta for the “both” cases in term of drag count

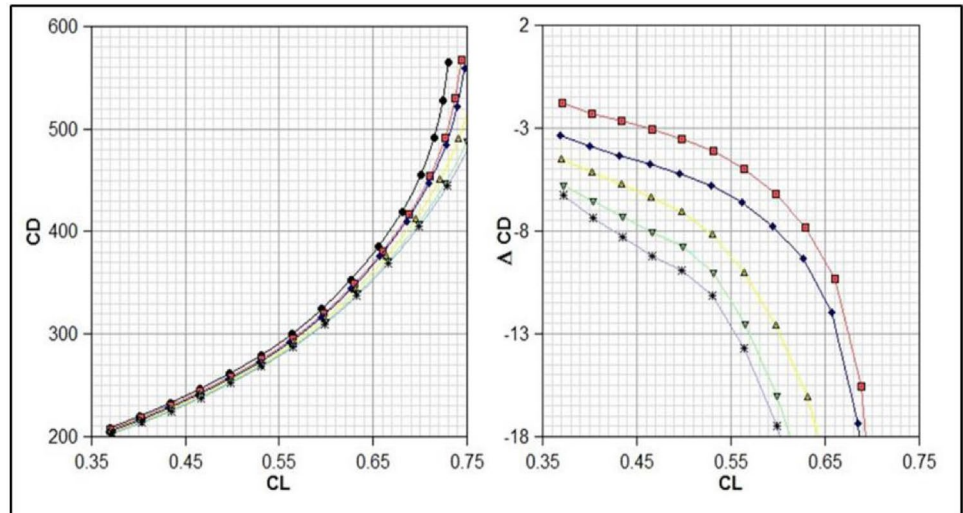


Fig. 12 Viscous drag for the “both” cases in term of drag count

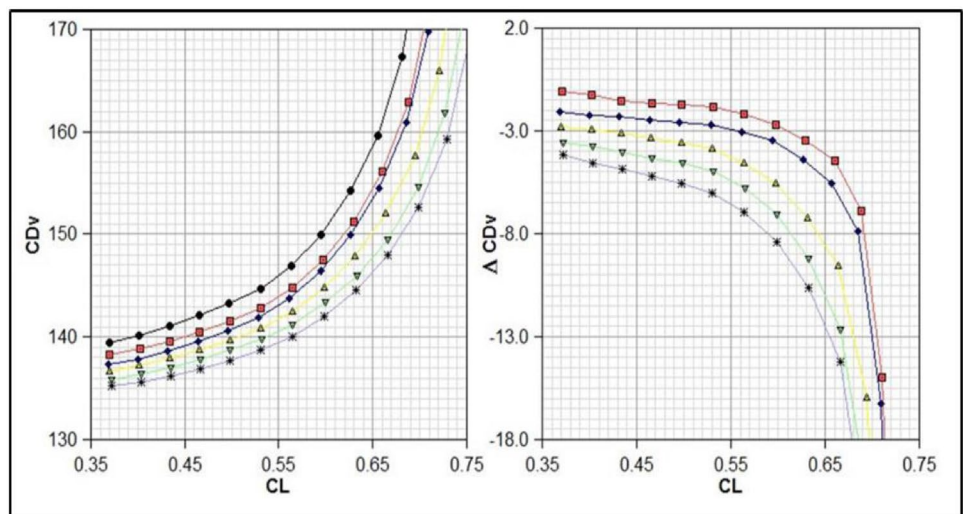


Fig. 13 Induced drag for the “both” cases in term of drag count

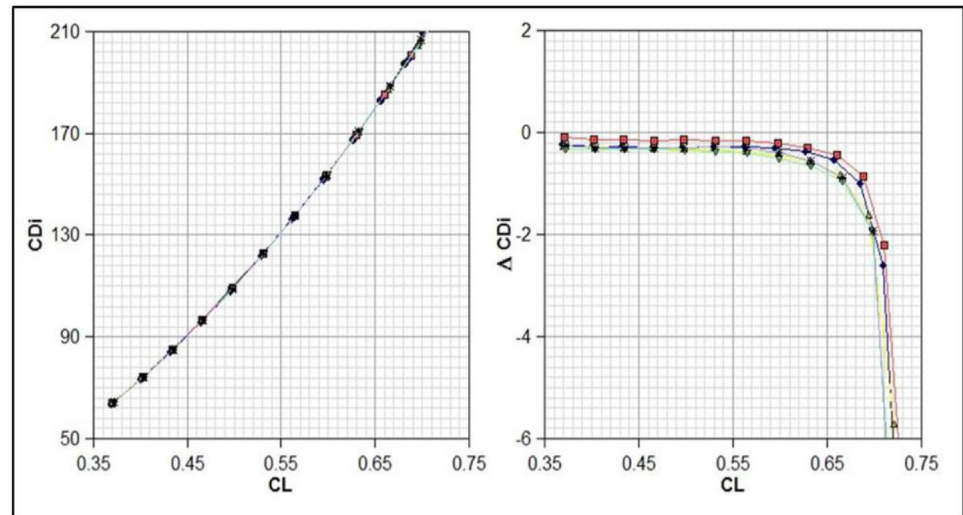
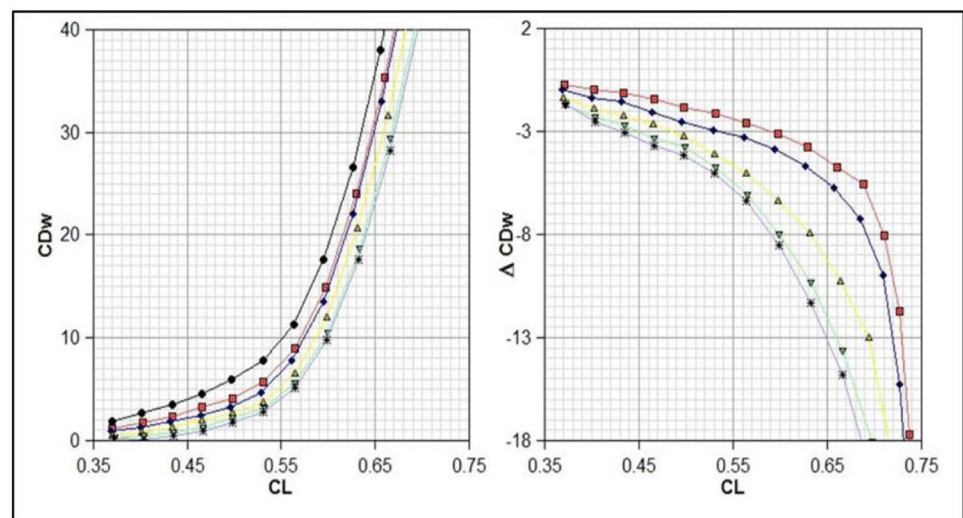


Fig. 14 Wave drag for the “both” cases in term of drag count



wing module enable to consider the cost impact of several technologies/design solutions for the structural elements of the wing. The module takes inputs from geometry, primarily high-level parameters to define the basic airframe, and from other domains to define the physical product such as number of parts, weights and etc. Moreover, they as input require shared project, program financial assumptions. They output manufacturing costs for the 100th development aircraft to DOC model, part count to define physical design task to design non-recurring-cost (NRC) model, parts lists, part count process type to define physical production engineering task to production NRC model. Major structural type, metallic or composite to the maintenance cost model for the wing module.

The cost analysis has been launched keeping constant the desired internal rate of return (IRR) for the manufacturer. Summary of results are reported in Table 3.

As it is possible to discern from Table 3, the wing recurring cost decreases accordingly with the reduction of the t/c and no difference is found between “both” and “low” cases as expected. Although the number of parts quantity does not vary with the reduction of t/c , the size of the components decrease, which implies less raw material to be used. Moreover, the quantity of fasteners for any part that attaches to the spars will reduce as t/c decreases (e.g. slat ribs and hold down ribs on leading edge, inter spar ribs in wing box), hence less fasteners are necessary for the assembly. Consequently, it means less labor time and all this translates in reduction of recurring cost. The fact that the IRR for the manufacturer is kept constant means that the aircraft price decrease proportionally. This translates in a better internal rate of return for the customer. Moreover, the better Direct Operating Cost achieved is not only due to the better aerodynamic

Table 2 Aerodynamic coefficients and the ratio L/D for the baseline and all “low” cases

Alpha	Baseline			3% low			5% low		
	Cl	Cd	L/D	Cl	Cd	L/D	Cl	Cd	L/D
0.50	0.369	0.021	17.736	0.388	0.021	18.119	0.399	0.022	18.366
0.75	0.402	0.022	18.254	0.419	0.023	18.549	0.431	0.023	18.735
1.00	0.433	0.023	18.328	0.451	0.024	18.845	0.463	0.024	18.983
1.25	0.465	0.025	18.878	0.483	0.025	19.027	0.494	0.026	19.124
1.50	0.497	0.026	19.004	0.515	0.027	19.093	0.526	0.027	19.153
1.75	0.530	0.028	19.003	0.547	0.029	19.036	0.559	0.029	19.061
2.00	0.536	0.029	18.785	0.579	0.031	18.775	0.591	0.032	18.774
2.25	0.595	0.032	18.350	0.612	0.033	18.310	0.623	0.034	18.292
2.50	0.620	0.035	17.745	0.642	0.036	17.686	0.653	0.037	17.657
2.75	0.655	0.038	17.024	0.671	0.039	16.959	0.681	0.040	16.924
3.00	0.681	0.042	16.234	0.696	0.043	16.168	0.706	0.044	16.132
3.25	0.701	0.045	15.400	0.715	0.047	15.340	0.724	0.047	15.304
3.50	0.715	0.049	14.544	0.729	0.050	14.505	0.740	0.051	14.494
3.75	0.724	0.053	13.712	0.738	0.054	13.691	0.751	0.055	13.711
4.00	0.730	0.056	12.918	0.745	0.057	12.927	0.755	0.058	12.929
Alpha	7% low			10% low			12% low		
	Cl	Cd	L/D	Cl	Cd	L/D	Cl	Cd	L/D
0.50	0.407	0.022	18.567	0.427	0.023	18.195	0.438	0.023	18.949
0.75	0.438	0.023	18.909	0.458	0.024	19.055	0.469	0.024	19.159
1.00	0.470	0.025	19.127	0.490	0.025	19.194	0.501	0.026	19.262
1.25	0.502	0.026	19.243	0.522	0.027	19.248	0.532	0.028	19.286
1.50	0.533	0.027	19.248	0.553	0.029	19.190	0.564	0.029	19.196
1.75	0.566	0.029	19.137	0.586	0.031	19.024	0.596	0.031	19.003
2.00	0.598	0.032	18.836	0.618	0.033	18.686	0.28	0.034	18.645
2.25	0.629	0.034	18.343	0.649	0.036	18.171	0.659	0.036	18.119
2.50	0.660	0.037	17.699	0.678	0.039	17.523	0.689	0.039	17.465
2.75	0.688	0.041	16.958	0.706	0.042	16.790	0.716	0.043	16.733
3.00	0.713	0.044	16.162	0.728	0.045	16.007	0.738	0.046	15.949
3.25	0.732	0.048	15.331	0.746	0.049	15.197	0.755	0.049	15.144
3.50	0.745	0.051	14.502	0.759	0.053	14.396	0.768	0.053	14.355
3.75	0.755	0.055	13.713	0.769	0.056	13.632	0.778	0.057	13.605
4.00	0.762	0.059	12.964	0.777	0.060	12.094	0.786	0.061	12.873

performance that in turn is translated in a less fuel consumption but also to the decrease of sale aircraft price, even if to a lesser extent. Although aircraft price is also influenced by other factors, such as fuel prices, tax rates, and leasing rates as well as airlines' negotiations with manufacturers and optional specifications these external factors are not considered in this study. On the other hand, it is clearly possible from the manufacturer to increase or keep constant the aircraft price without having a negative effect. In general, airlines are willing to pay higher prices for new aircraft if they can lower operating costs by adopting more-fuel efficient, advanced technology. A further analysis has been carried on in order to check the

effect of aerodynamic performance in term of spanwise loading. The next Figs. 21 and 22 show the aerodynamic load over the wing for the “both” and “low” cases calculated at cruise.

It is evident from the figures above that for the “both” cases, the spanwise loading does not vary much with the t/c variation. On the contrary, for the “low” cases the spanwise loading increases when the wing is thinner. This means that the structure has to withstand higher loads and therefore, the weight of the wing has to increase accordingly due to a larger wing box sizing. Therefore, the DOC benefit gained due to better aerodynamic performance comes at the expense of a higher loading on the wing.

Fig. 15 Lift polar and relative CL delta for the “low” cases

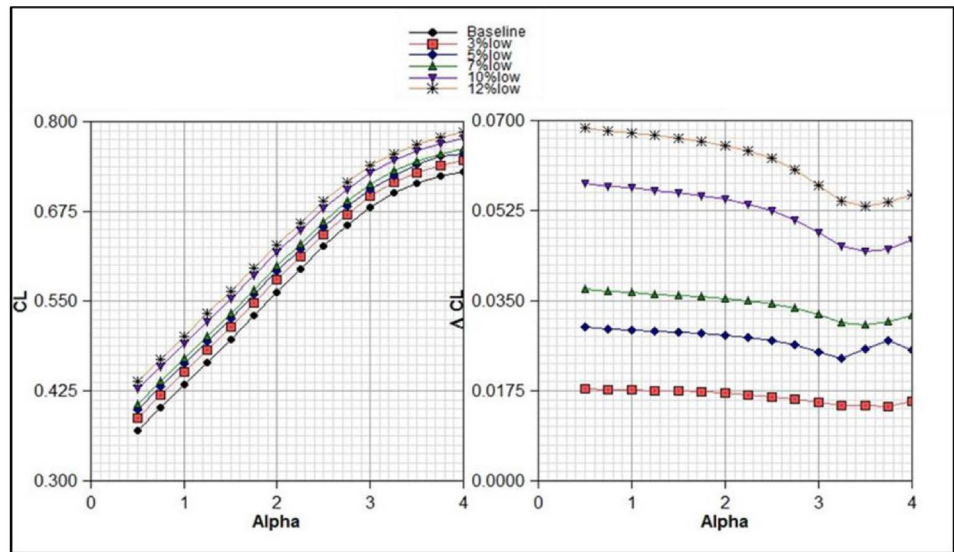


Fig. 16 Drag polar and relative Cd delta for the “low” cases in term of drag count

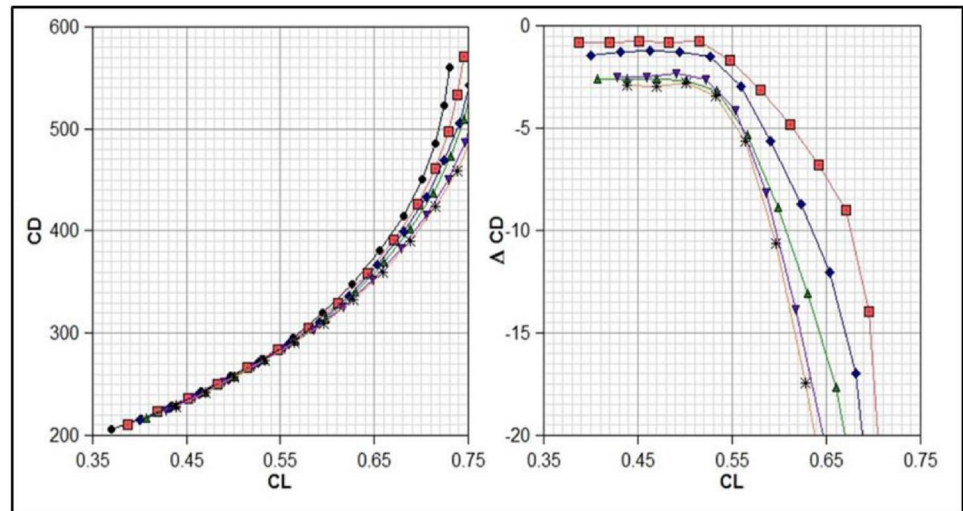


Fig. 17 Viscous drag for the “low” cases in term of drag count

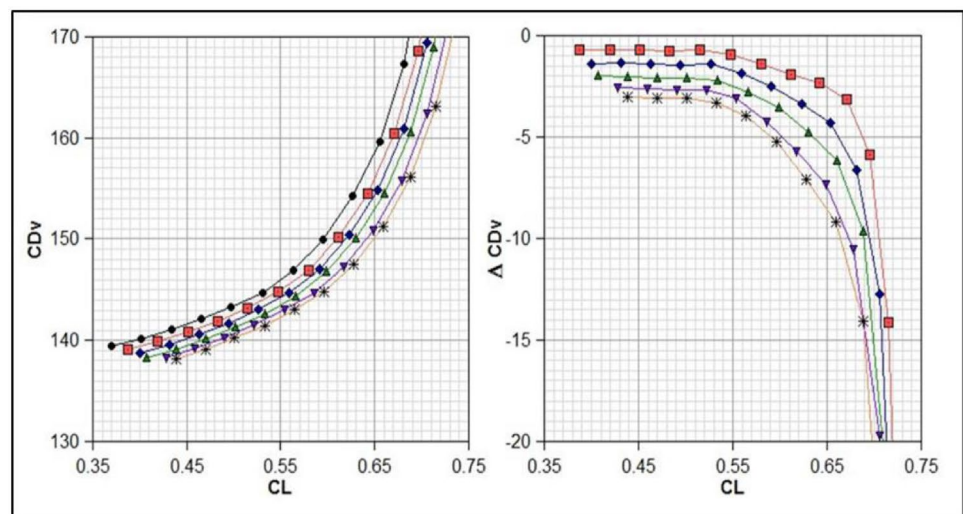


Fig. 18 Induced drag for the “low” cases in term of drag count

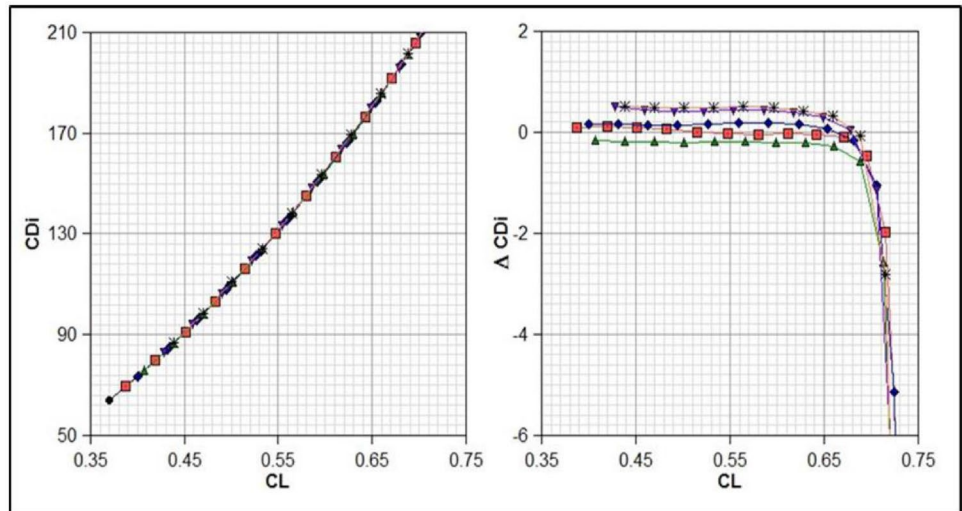


Fig. 19 Wave drag for the “low” cases in term of drag count

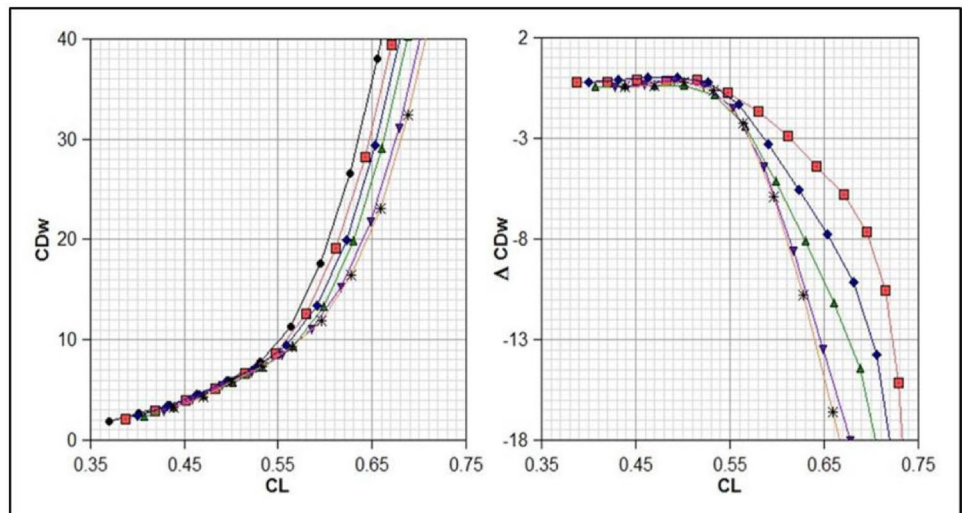


Fig. 20 DOC function of the thickness over chord variation

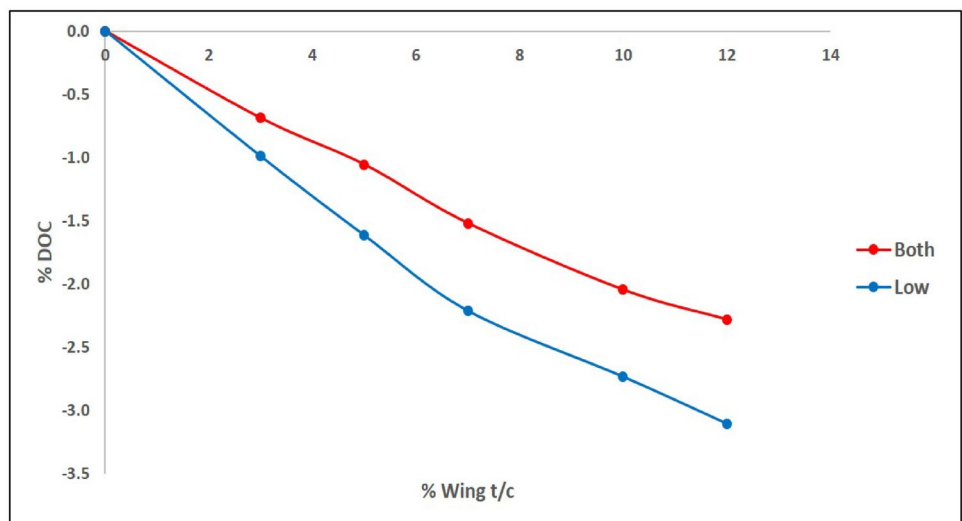


Table 3 Financial summary results for all cases investigated

	Δ Wing cost	Δ Sale price	IRR (air-line)	IRR (manu-facturer)	Δ DOC
BSL	0.00%	0.00%	6.00%	6.00%	0.00%
3%both	-0.61%	-0.69%	6.34%	6.00%	-0.688%
5%both	-1.05%	-0.86%	6.52%	6.00%	-1.056%
7%both	-1.59%	-1.06%	6.74%	6.00%	-1.520%
10%both	-2.29%	-1.34%	7.00%	6.00%	-2.047%
12%both	-2.75%	-1.52%	7.12%	6.00%	-2.283%
3%low	-0.61%	-0.72%	6.48%	6.00%	-0.991%
5%low	-1.05%	-0.86%	6.67%	6.00%	-1.616%
7%low	-1.59%	-1.06%	7.05%	6.00%	-2.213%
10%low	-2.29%	-1.34%	7.31%	6.00%	-2.735%
12%low	-2.75%	-1.52%	7.49 &	6.00%	-3.105%

6 Conclusions

It is clear that to analyse overall aircraft performance, it is important to consider both aerodynamic efficiency and financial implications simultaneously, to account for the interaction and trade-offs between the two disciplines. In the present work, the impact of aircraft aerodynamic performance on aircraft Direct Operating Cost and price have been quantified. In general, improvements in aircraft aerodynamic performance lead to reductions in direct operating cost. However, here, economic behaviors have

been described by only a few simplified parameters. For the full assessment of an aircraft configuration, it will be essential to consider all relevant costs and disciplines for their interactions on overall aircraft performance. In fact, the cost suite has been integrated using an integration framework that has the capability to be automatically linked with external domains, providing a means to take input from other domain tool sets [12]. In this way, the cost model that can be treated as a component of a larger computational design process, could be implemented in a multidisciplinary process allowing a trade-off between weight, aero performance, and cost. Several research activities have been carried out in aero-structural optimization such as [16–20], to take into account aero-elastic effects, in order to simultaneously optimize the aerodynamic shape and structural sizing. Coupling aerodynamic and structural numerical models to compute the static aeroelastic shape of aircraft wings is essential especially when designing wings that are flexible. Indeed, the structural design in modern commercial aircrafts inevitably involves considerations of aerodynamic performance. Integrating the aero-structure interactions with the current framework will allow the designing for a better overall aircraft efficiency and Multi-disciplinary trade-off techniques can reduce the weight and cost of an aircraft design concept in the preliminary design phase by fairly minor changes to the key design variables. The proposed work offers a strong basis for further development.

Fig. 21 Spanwise loading for “both” cases at cruise

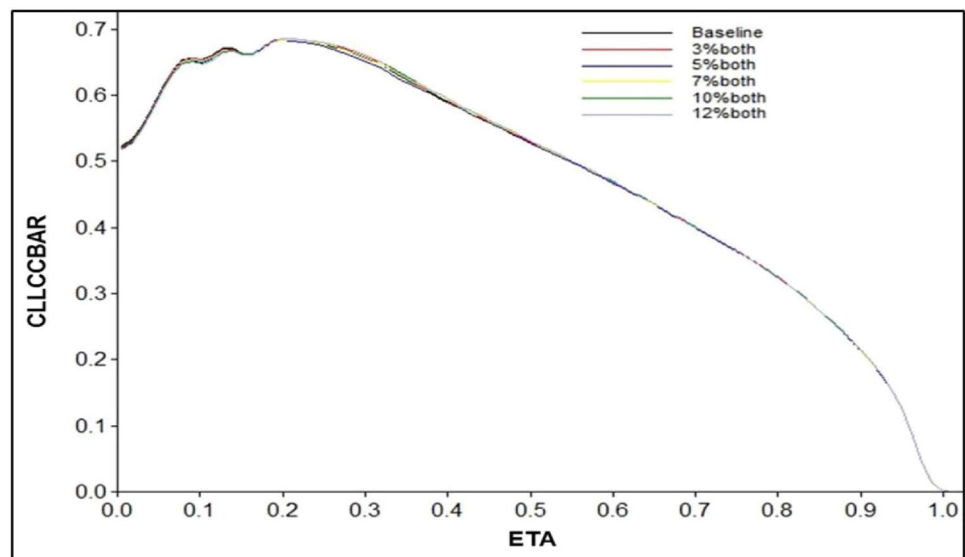
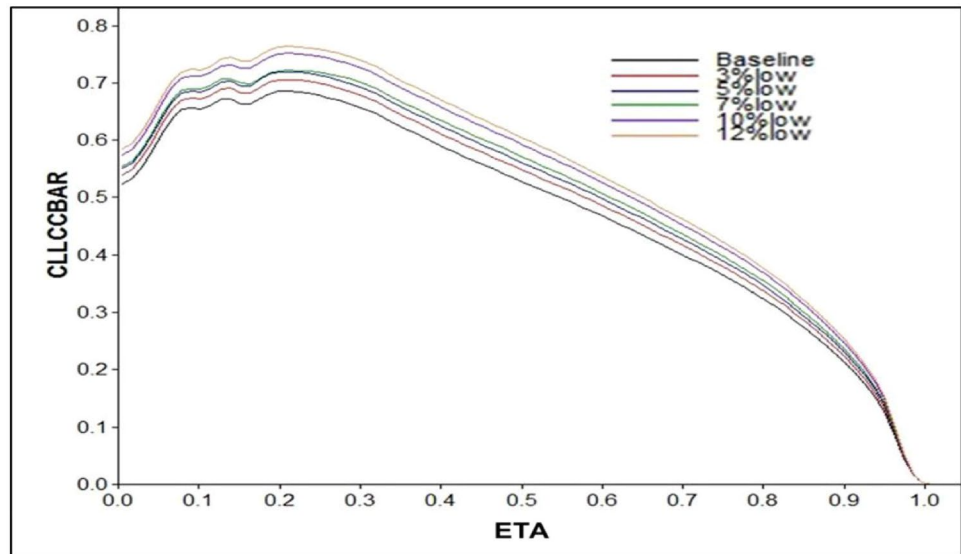


Fig. 22 Spanwise loading for “low” cases at cruise



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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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