The importance of coupling aerodynamic and cost analysis in aircraft design

Davide Di Pasquale1 · Mark Savill2

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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
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 overspending 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
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supplier decision-making to improve manufacturing qual-
ity by minimizing faults [8]. However, infrequently previ-
ous research has dealt with the integration aspect as part of a centrally driven systematic workflow that enables col-
laborative 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 tech-
nology, 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 pic-
ture. 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 methodolo-
gy for the generation of a cost estimation approach for pre-
liminary 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 environ-
ment 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 explana-
tion of the different cost categories acknowledged as being
sustained by an aircraft manufacturer, including the main
cost requirements that should be included into a multidisci-
plinary design process to achieve an economic and efficient
aircraft, together with an overview of different cost model-
ling 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 finan-
cial 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 busi-
ness sense. The coupled performance/financial framework
enables an integrated approach to technical design and pro-
grammatic decisions. The objective of this work is to couple
toeroformance 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 profi-
tability, it receives the most attention because several fac-
tors 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

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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
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
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.

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
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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-induce 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.

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

where $W_{\text{fuel}}$ is the carried fuel weight $W_{\text{PL}}$ 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
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

| Table 1 | Aerodynamic coefficients and the ratio L/D for the baseline and all “both” cases |
|---------|---------------------------------|---------------------------------|---------------------------------|
| **Alpha** | **Baseline** | **3% both** | **5% both** | **7% both** | **10% both** | **12% both** |
| **Cl** | **Cd** | **L/D** | **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** | **Baseline** | **5% both** | **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 | 0.021 | 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 |
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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
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
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...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.

| 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  | 19.124 |
| 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 |
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
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.

| Table 3 | Financial summary results for all cases investigated |
|---------|-----------------------------------------------------|
|         | Δ Wing cost | Δ Sale price | IRR (airline) | IRR (manufacturer) | 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%           |

Fig. 21 Spanwise loading for “both” cases at cruise
The importance of coupling aerodynamic and cost analysis in aircraft design

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Declarations

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

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