A CONCEPTUAL DESIGN AND ANALYSIS METHOD FOR CONVENTIONAL AND UNCONVENTIONAL AIRPLANES

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Abstract

A design method is presented that has been implemented in a software program to investigate the merits of conventional and unconventional transport airplanes. Design and analysis methods are implemented in a design tool capable of creating a conceptual design based on a set of top-level requirements. In contrast to established design methods, emphasis is placed on designing unconventional as well as conventional airplane configurations. A parametric fuselage primitive and a parametric lifting-surface primitive have been defined. By combining various instances of these primitives, airplane geometries ranging from blended-wing-body configurations to three-surface configurations can quickly be generated. Analysis methods have been developed/refined such as to enable the (physics-based) disciplinary analysis of conventional and unconventional airplane concepts. Design rules have been implemented to automatically size the main airplane components. This paper describes the workings of the software tool, presents relevant validation studies and showcases a comparison study between five different airplane configurations.

List of symbols

A	Wing aspect ratio
b	Wing span
e	Span efficiency factor
L/D	Lift-to-drag ratio
S	Wing planform area
λ	Wing taper ratio
$\Lambda_{0.25c}$	Wing sweep angle
μ	Arithmetic mean
σ	Standard deviation

1 Introduction

Since the conception of powered flight in the early 20th century, we have been conceiving many different airplane configurations ranging from propeller-powered triplanes to jet-powered flying wings. However, over the past six decades only one airplane configuration has dominated the high-subsonic transport category: the tube-and-wing (TAW) configuration. For this configuration, there exist essentially two variations: one with the engines under the wing usually in combination with a conventional tail (e.g. Airbus 320 and Boeing 747) and one with engines attached to the fuselage usually in combination with a T-tail (e.g. Fokker 28 and DC-9). Other, less conventional configurations have been demonstrated to work well in other categories. For example, the flying-wing configuration was applied in the military domain to the B-49 and the B-2. Canard configurations have been implemented in both the military domain and general aviation (e.g. Rutan's VariEz or Starship). The three-surface configuration of the Piaggio Avanti even resulted in a propeller-powered airplane rivaling its jet-powered competitors for cruise speed, while having a relatively low specific fuel consumption. This begs the question: how do these unconventional airplane configurations compare to their conventional counterpart in the high-subsonic transport category?

To answer this question using data from the open literature poses several challenges. First of all, finding two airplanes that have been designed for exactly the same top-level requirements and design-objective is impossible. A comparison is therefore never completely fair. Secondly, comparing unconventional configurations that only exist on paper (e.g. the blended-wing-body airplane) to existing conventional airplane can also not be fair. For the paper airplane, only prediction tools can be used to estimate the key performance indicators (KPIs), while for existing airplane the KPIs can be measured. Only when two airplane configurations are analyzed using the same analysis methods, can one compare them correctly. This ties in closely to the third challenge: using applicable analysis methods. While some analysis methods can be employed on any generic airplane configuration, other analysis methods (e.g. weight estimation methods) usually have an empirical component and can therefore only be applied to airplanes of the same configuration. In other words, appropriate analysis methods that are suitable for the conceptual design phase of both conventional and unconventional airplane configurations are not readily available.

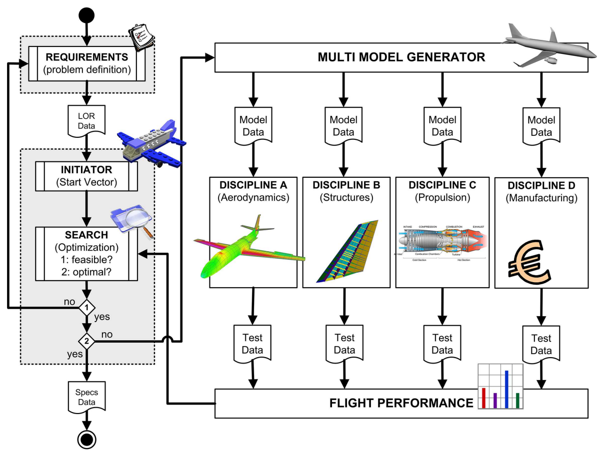


Fig. 1 Flowchart of the Design and Engineering Engine

Given these challenges, the authors believe that the only way to determine the merit of new airplane configurations, is by developing design and analysis tools that can be applied to both conventional and unconventional airplanes. For that purpose, the concept of the Design and Engineering Engine (DEE) was conceived. The DEE is an advanced design system to support and accelerate the design process of an airplane and/or its subcomponents by automation of non-creative activities involved in the design process. The DEE also provides optimization capabilities both to improve the design and handle novel configurations with complex and non-intuitive design parameters. A flowchart of the DEE can be found in Figure 1 [1]. At the heart of the DEE framework is a fully parameterized geometric model of the airplane called the Multi Model Generator (MMG). This geometry is automatically translated to appropriate input files for a variety of disciplinary analysis tools of both low and high fidelity. The analysis results are used in a constrained optimization to alter the design variables such as to achieve a certain design objective. An extensive description of the DEE can be found in La Rocca (2011) [2] and La Rocca and Van Tooren (2007) [1]. A design initiator (referred to as *Initiator*) has been developed that translates top-level requirements (TLRs) in combination with a chosen design configuration and design objective into a first estimate of the airplane's geometry and calculates the associated performance indicators. As described by La Rocca *et al.* (2012) [3], the *Initiator* itself works like a small DEE, only having less design parameters and being coupled to only low-fidelity disciplinary analysis methods. Due to the low computational cost of the analysis methods, the optimization process in the *Initiator* can quickly find a constrained optimum for a predefined figure of merit.

The foundation of the initiator was established in 2011 and is described by Van Dommelen and Vos (2014) [4] and by La Rocca *et al.* (2012) [3] The present paper presents the structure and content of the *Initiator* and demonstrates how it can be applied to conventional and unconventional airplanes. Emphasis is placed on the generic parameterization method of the airplane shape, the newly developed analysis methods, validation of the the analysis methods, and implementation of the framework in the MATLAB environment. Use cases are presented to demonstrate the functionalities of the *Initiator*.

2 Description of the Design Tool

The *Initiator* is a design tool which is able to generate a conceptual airplane design based on a set of TLRs. The purpose of the design tool is the synthesis of unconventional as well as conventional jet transport airplanes. There is little statistical data on unconventional airplane configurations, therefore typical empirical tools are of little use in the conceptual design phase. The usage of physics-based methods is preferred, however such tools generally require some geometrical input and take more computational resources than simple empirical relations. In those cases, the choice of analysis tools for the assessment of the performance of the generated airplanes is a trade-off between fidelity, design sensitivity and runtime. This trade-off is made for every discipline and a balance is struck between introducing enough design-sensitivities to be able to adequately model the different configurations while keeping the extra computational effort within reasonable limits (a maximum of 5-10 seconds per method, resulting in a converged airplane design within 10 minutes).

2.1 Definition of High-Level Primitives

Since most methods employed in the *Initiator* require geometrical input, a 3D-representation of the airplane is generated as soon as the most basic parameters (overall weight and aerodynamic performance) are calculated. All airplane configurations can be modeled using an assembly of parameterized geometry blocks called *high-level primitives* (HLPs). Two HLPs have been developed which are used to define the main architecture of the different airplane configurations.

The first HLP is the lifting surface, which consists of a variable number of trunks that each have a certain span, aspect ratio, taper, and sweep angle. Furthermore, the airfoil shape at the beginning and end of the trunk is specified as well as the corresponding thickness-to-chord ratio and incidence angle. This primitive is used for all lifting surfaces on the airplane (e.g. wing, canard, tail surfaces, winglets).

The second HLP describes the fuselage. For this primitive one needs to specify the crown and belly curve of the fuselage in combination with the main-deck width at a variable number of fuselage stations. Based on this input, a circular or oval fuselage can be generated, depending on the user input. The oval fuselage forms the basis for the blended-wing-body designs [5]. In addition to these two HLPs, simple primitives are defined for engines, cargo containers, spars, fuel tanks and landing gear.

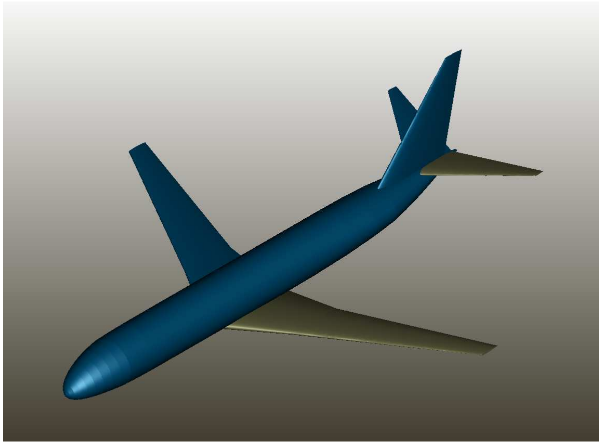
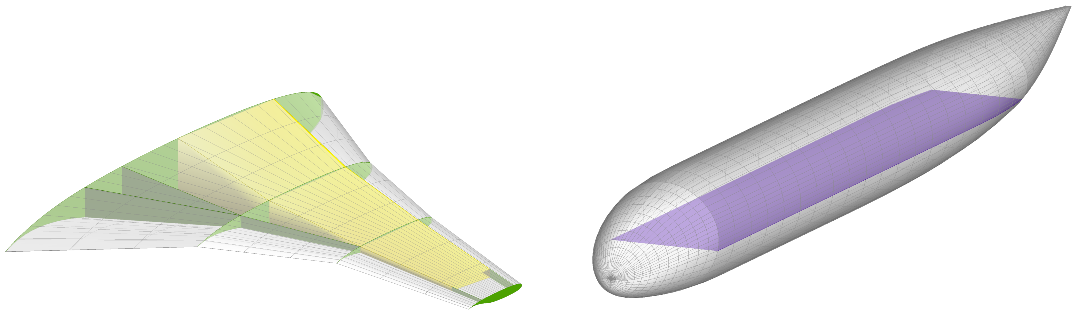


Fig. 3 CPACS output generated by *Initiator*

2.2 Software Implementation

The *Initiator* is implemented in an object-oriented fashion in the MATLAB environment. At the core of the program is an object called the *controller*, which is responsible for the process flow in the *Initiator*. All design and analysis tools are implemented as objects called *modules*. Dependencies can be assigned to each of these modules such that a design and analysis workflow can be defined. For example, if the aerodynamic analysis module is called, the controller automatically runs all the modules that are required to generate the input parameters for this module. The controller also tracks the dependencies between modules to make sure no computational resources are used to re-calculate modules whose input did not change. All input, output and setting data transfer via a single XML-file. This creates a clean interface between each of the modules and allows a straightforward translation to other XML-based formats such as CPACS [6]. In Figure 3 a CPACS-file generated by *Initiator* is visualized.



(a) Wing HLP (b) Fuselage HLP

Fig. 2 Example of the main high-level primitives used in the *Initiator*

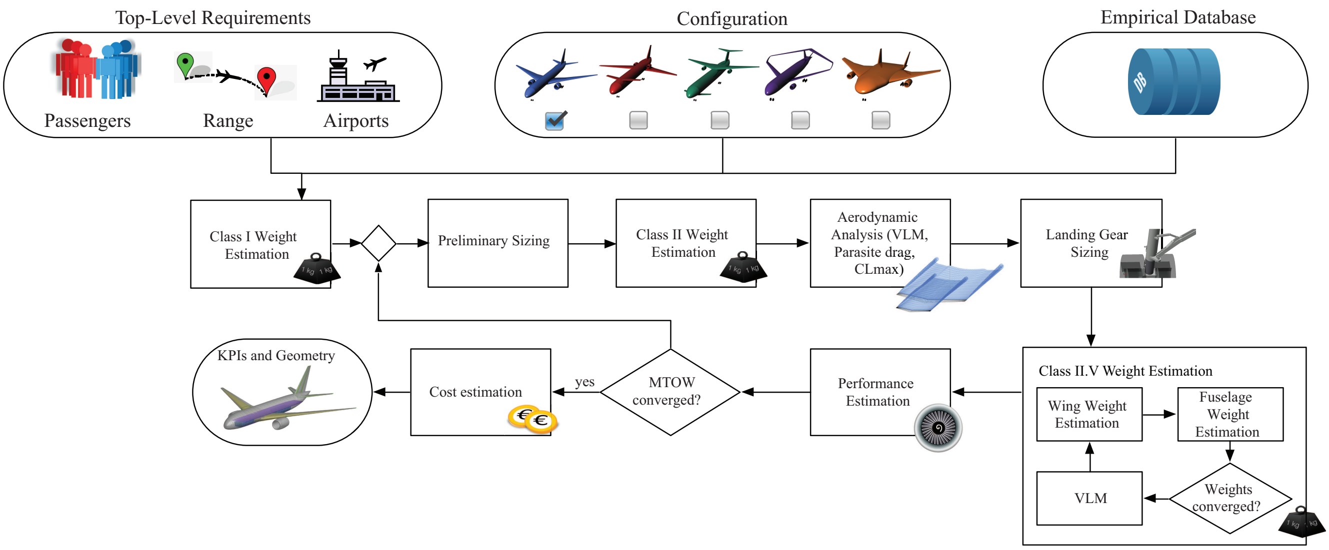


Fig. 4 Schematic process diagram of the *Initiator*.

3 Airplane Synthesis Methods

The airplane synthesis work-flow (Figure 4) is based on the conventional conceptual design process where a first estimate of the airplane weight and performance is made, first using Class I methods based on the TLRs. With these preliminary results more refined methods (Class II and II.V [7]) are used to get a more accurate representation of the airplane. This process is repeated until the maximum take-off weight (MTOW) does not change by 0.5% with respect to the weight calculated in the previous iteration.

3.1 Preliminary Sizing

The design process starts with the specification of a set of top-level requirements: payload weights (passengers and cargo), range requirements, field lengths and altitudes, cruise speed and cruise altitude. In addition, extra requirements can be imposed such as climb rates, sustained turn rates, as well as additional payload-range combinations. The regulatory requirements (CS-25) are also specified and are used in the preliminary design.

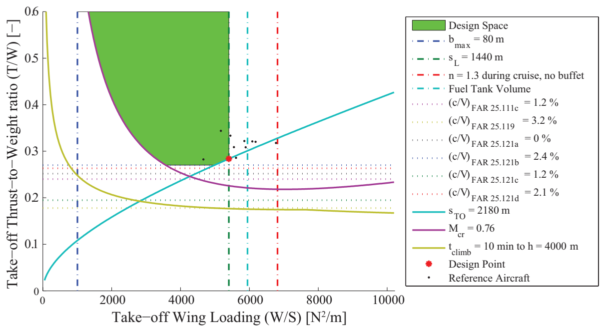


Fig. 5 Wing loading - Thrust-to-weight ratio diagram

The preliminary sizing of the airplane starts with a Class I weight estimation. Using Torenbeek's "lost range" method [8] the fuel fraction of the combined climb, cruise and descent phase is calculated. References from a database are used to estimate the operational empty weight (OEW) based on the payload and range requirements. This database can contain either existing airplane designs or designs previously generated by the Initiator. The most convenient combination of wing loading and thrust-to-weight ratio is determined taking into account the aerodynamic, operational and regulatory constraints (See Figure 5). Based on the estimated airplane weight and surface area the geometry is created by instantiating the required HLPs, which are sized using the payload requirements and airplane design rules using volume coefficients as described by Raymer [9].

3.2 Component Weight Estimation

The airplane weight is calculated with Class II methods from Raymer [9] augmented with physics-based Class II.V methods for the wing and fuselage as described in the following subsections. The fuel weight is recomputed by evaluating the mission profile with the available drag polar from the aerodynamic analysis and engine performance data. This results in a new maximum take-off weight and closes the design loop as seen in Figure 4.

Wing Weight

The wing weight is estimated by using the *EMWET* tool developed by Elham [7, 10]. This program implements a quasi-analytical wing weight estimation method which uses load data from an aerodynamic analysis at 2.5g loading to calculate the required material distribution in the primary structure (the wing box) to withstand the loads. A single empirical relation between the primary and secondary structures is used to calculate the total wing weight. The strength of this method is its sensitivity to the planform and airfoil shape, the position of the spars and the aerodynamic load and moment distribution.

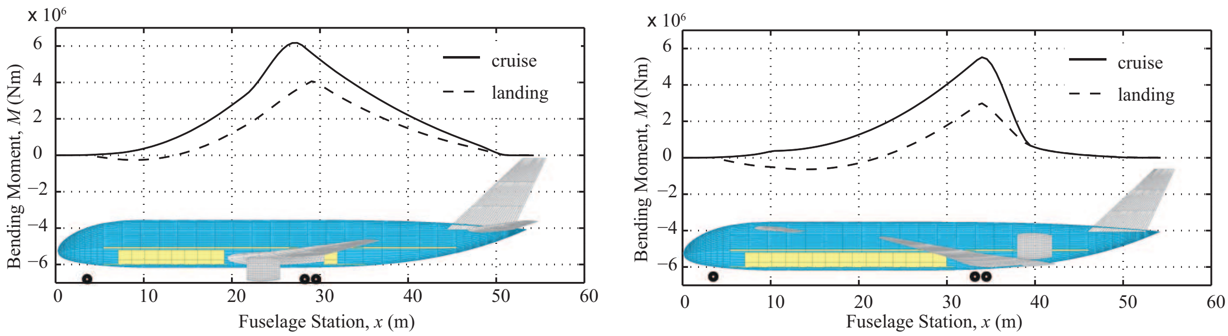
Fuselage Weight

The fuselage weight estimation (developed by Schmidt [11] and Hoogreef [12]) is a quasi-analytical method which uses the aerodynamic loads as well as the airplane component weights to estimate the loads on the fuselage for ten different load cases. The maximum and minimum load factor (2.5g and -1g) are considered at the harmonic range payload-range condition (maximum payload, fuel added until MTOW is reached) and the maximum fuel condition (maximum fuel, payload added until MTOW is reached). For each of these four scenarios two load cases for the difference between ambient and cabin pressure are created: the maximum differential pressure and zero pressure difference. In addition, two load cases (with and without pressurization) are included for hard landing at design landing weight. These load cases are used to size the equivalent thickness of the outer shell of the fuselage. Semi-empirical relations for the various secondary structures and non-structural weights are used to calculate the total fuselage weight. This weight estimation method is sensitive to relevant design variables such as wing positioning and landing gear placement. In Figure 6 the bending moment distribution on the fuselage can be seen for a conventional airplane and an airplane with a canard configuration. This distribution has great influence on the fuselage weight, as is also shown in the design of the RECREATE *cruiser* airplane [13] as discussed in Section 5.

3.3 Aerodynamic Analysis

The aerodynamic analysis is performed by three separate modules. The lift-dependent drag of the airplane in trimmed condition is calculated using the Athena Vortex Lattice (AVL) program written by Drela[1]. This method is also used for estimating the aerodynamic loads on the lifting surfaces which are required for the Class II.V weight estimation methods described in Section 3.2. Since this is an inviscid analysis method, the friction drag needs to be estimated with a

[1] M. Drela. AVL 3.32, http://web.mit.edu/drela/Public/web/avl/



(a) Conventional (b) Canard

Fig. 6 Example output of the Class II.V fuselage weight estimation

different method. The parasite drag and wave drag contributions are calculated using an empirical method as described by Roskam [14]. By combining all drag contributions the drag polar of the airplane can be constructed. To determine the maximum lift coefficient ($C_{L_{\max}}$) of the clean wing, a semi-empirical method (ESDU 89034 [15]) is used. An estimation method for the performance of high-lift devices such as flaps and slats is under development. The version of the *Initiator* presented in this paper uses an increase in maximum lift ($\Delta C_{L_{\max,\mathrm{HLD}}}$) with respect to the calculated clean maximum lift coefficient and a variation in the span-efficiency factor (Δe_{HLD}) for the different high-lift configurations.

3.4 Landing-Gear Sizing

The position of the landing gear is limited by constraints imposed by take-off and touchdown stability, wing tip and nacelle clearance and ground operations (turn radius, nose gear loading and wheel base). From the database (with 342 different tyres) the tire with a suitable rated load is selected. This rated load includes a tire safety factor (1.25 by default). The bogie layout is varied such that the tire-bogie combination results in the least complex design (the least amount of wheels). Within the feasible design space, the landing gear position which results in the shortest landing gear is selected.

3.5 Engine Sizing and Performance

The engine sizing and analysis module is based on the modeling method for hybrid turbofan engines presented by Tang [16]. This method has been modified to enable the analysis a conventional turbofan engine. Common engine parameters such as by-pass ratios, turbine inlet temperatures and pressure ratios are local design parameters. The engine thrust is determined from the thrust-to-weight ratio calculated in the preliminary sizing phase. The engine is sized using engine diameter as a variable until the required thrust is met. This results in a prediction of the specific fuel consumption of the engine.

3.6 Cost Estimation

The *Initiator* includes a module to perform a cost estimation for the design, production and operating cost. The module uses a bottom-up approach, calculating the cost price for every airplane component based on the calculated weights. For a pre-defined production quantity, the non-recurring [17], recurring [18] and unit cost of the airplane are estimated which result in a list price. The direct operating cost (DOC) and indirect operating cost are determined using empirical relations [17, 19] The accuracy of the module is highly dependent on the statistical data which are the base for the relations used in the calculations.

4 Design Tool Verification

The *Initiator* is a tool intended to synthesize a preliminary airplane design from a set of top-level requirements. Since commercial transport airplanes are the result of a design process with a generally unknown objective it cannot be expected from the *Initiator* to exactly match an existing airplane given the same top-level requirements. Still using existing airplanes as a reference, the design tool design capabilities can be verified. On the other hand, each of the aforementioned analysis tools have been validated individually [7–9, 11, 14, 16]. A selection of references varying from single-aisle regional jets to wide-body, long-range, jet-powered airplanes is made with different wing and engine configurations. Their TLRs are used to synthesize a design using the *Initiator*. Since errors in the weight estimation, aerodynamics and engine performance propagate in the design loop and result in a change in structural weight and fuel consumption, the airplane weight at the end of the design loop is a good indication of the performance of the total design tool. A comparison between the characteristic weights for the real airplane and the synthesized airplane can be seen in Figure 7 and Table 1.

Table 1 Errors in the estimation of the characteristic weights

	μ	σ
MTOW	10.8%	7.2%
OEW	11.1%	9.9%
OEW/MTOW	4.8%	3.9%

In addition to the characteristic weights, the geometry of the generated aircraft is compared with their existing counterparts. The top-view of such comparison can be seen in Figure 8. The sizing of the wing and tail surfaces gives a design comparable with the "real" airplane planforms. However, the fuselage sizing differs significantly for the various airplanes. Note that the designs shown in Figure 8 are all generated with the same sizing rules and settings. The placement of the engines is currently kept at a fixed percentage of the span, which explains the outboard engine placement of the A340 and the BAe 146.

An airplane with top-level requirements (Table 2) similar to an Airbus A320-200 is compared against reference data in Table 3. This airplane is used as the baseline in the comparison study discussed in Section 5.

Table 2 Top-level requirements of an airplane similar to the Airbus A320-200

Requirement	Value	Unit
Number of Pax (3 class)	150	-
Payload weight	20767	kg
Cruise Mach number	0.76	-
Cruise Altitude	11278	m
Cruise Range	2870	km
Take-off distance	2180	m
Landing distance	1440	m
Number of cycles	10^5	-
Loiter time	30	min
Divergence range	500	km
Wing aspect ratio	9.39	[-]

Table 3 Comparison of the A320-200 generated with the *Initiator* with data from Roux [20] and Obert [21]

	Initiator	Reference	Difference
b [m]	34.2	33.9	-0.9%
S [m^2]	124	122	-1.6%
λ [-]	0.215	0.246	12.6%
$\Lambda_{0.25c}$ [deg]	24.5	25.0	2.0%
mac [m]	4.37	4.19	-4.3%
MTOW [kg]	68400	73500	6.9%
OEW [kg]	35710	39733	10.1%
Fuel (max PL) [kg]	11930	13000	8.2%
MTOW/S [kg/m^2]	551	600	8.2%
OEW/MTOW [-]	52.2%	54.1%	3.4%
Fuel/MTOW [-]	17.4%	17.7%	1.4%
C_{D_0} [cts]	195	190	-2.6%
e	0.79	0.79	0.0%

The aerodynamic modules are validated by analyzing the exact geometry of an airplane with the *Initiator* aerodynamic modules and comparing them to flight test data [21]. Note that there is still a dependency on the weight estimation, since the trim drag is dependent on the position of the center of gravity. The resulting drag polars can be seen in Figure 9. Since the drag polar in the *Initiator* is represented by the equation $C_D = C_{D_0} + kC_L^2$, the slope of the $C_D - C_L^2$ curve

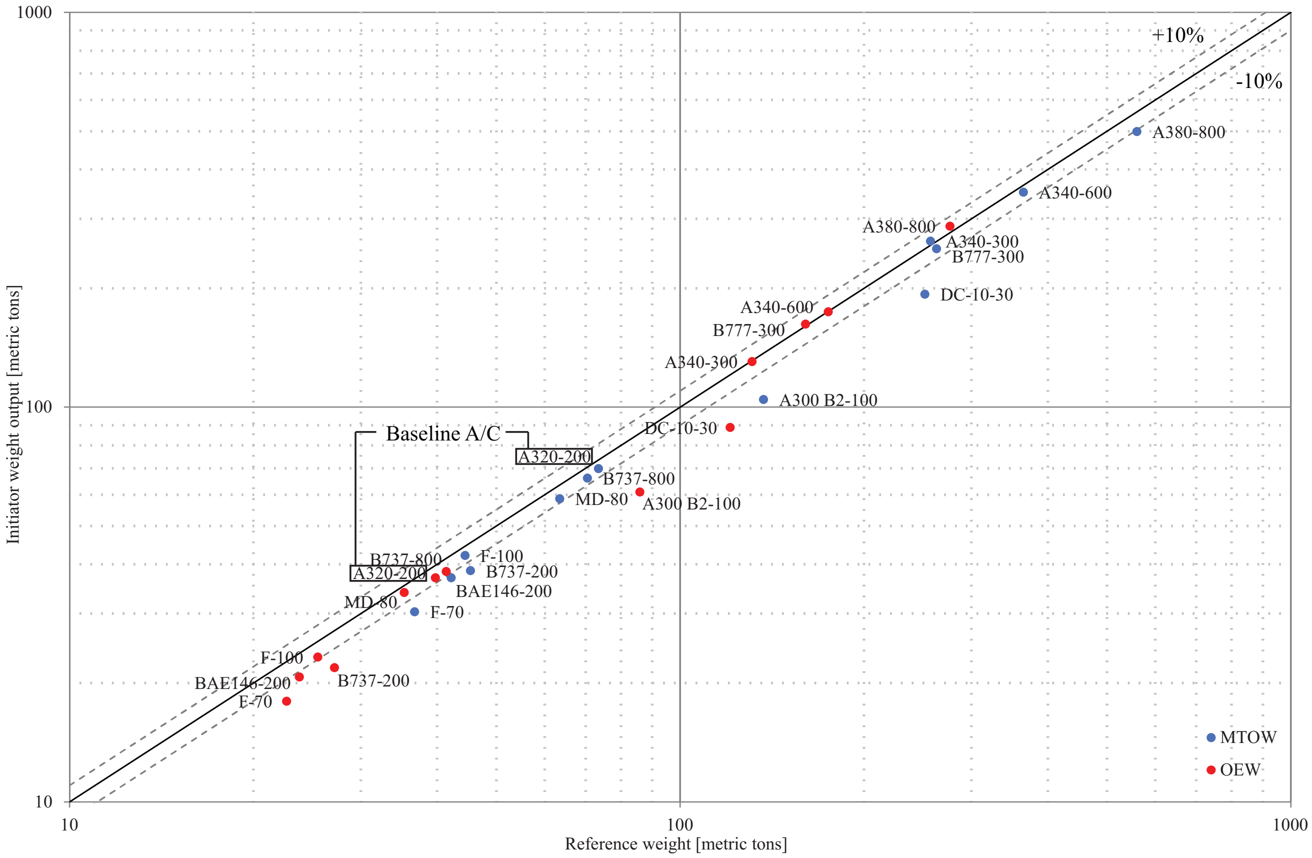
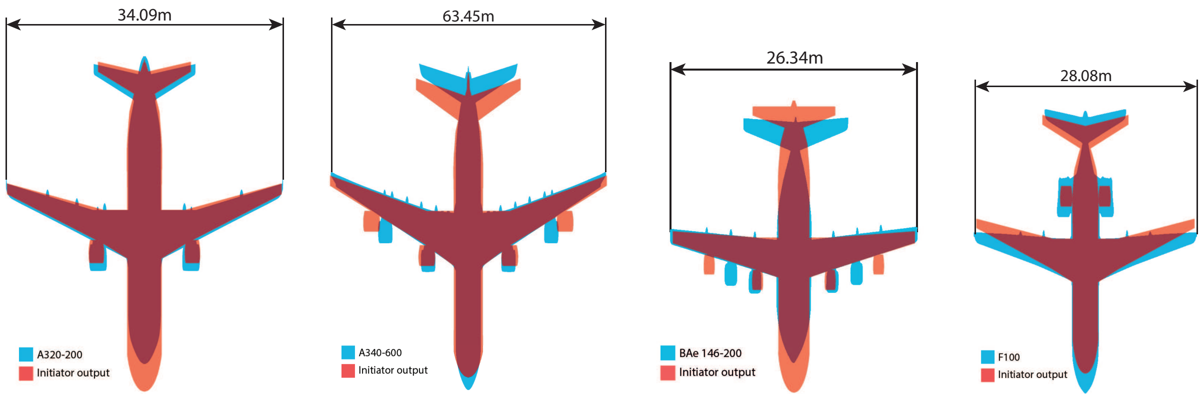


Fig. 7 Comparison of the maximum take-off weight (MTOW) and operational empty weight (OEW) between calculated values from the Initiator and reference aircraft weight data [20]



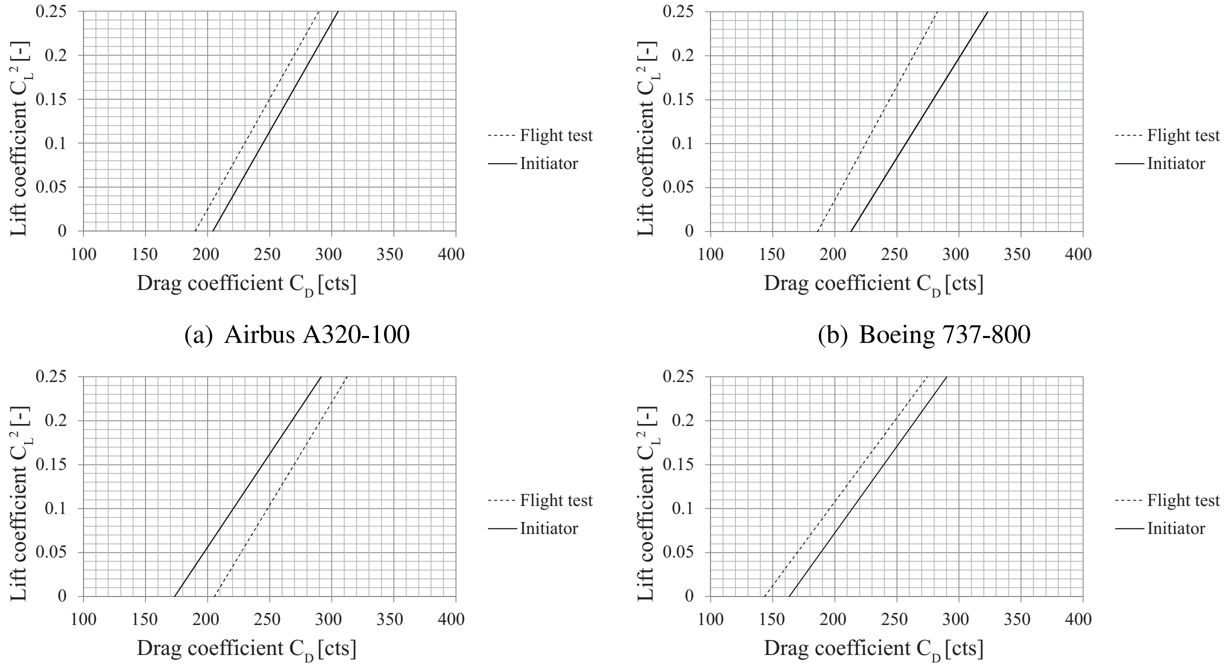
(a) A320-200 (b) A340-600 (c) BAe 146-200 (d) Fokker 100

Fig. 8 Comparison between the airplane top-views of the generated airplane (red) and the real airplane (blue)

shows the accuracy of the estimation of the k parameter ($k = (\pi A e)^{-1}$), the offset at the $C_L^2 = 0$ axis shows the accuracy of the zero-lift drag estimation. An overview of the errors can be seen in Table 4.

Table 4 Errors in the estimation of the airplane drag

	μ	σ
C_{D_0}	12.8%	3.7%
k	7.3%	6.0%



(a) Airbus A320-100

(b) Boeing 737-800

(c) McDonnell Douglas MD-80

(d) McDonnell Douglas DC-10-30

Fig. 9 Comparison of the drag polars of four different airplanes

5 Example of Comparison Study

To demonstrate the capability of the *Initiator*, the following use case is defined: an aircraft is to be designed with top-level requirements similar to the Airbus A320. A list of the requirements used as input for the design tool can be found in Table 2. The design objective is to minimize the fuel consumption over the harmonic range.

To fulfill these requirements, four different configurations were investigated. The selected configurations are the conventional TAW configuration, a canard configuration, a three-surface configuration (both a canard and a horizontal tail) and a box-wing (Prandtl) configuration.

Each of these configurations is designed and analyzed using the method of Section 2. The top views and a 3D-view of the generated configurations can be found in Figures 10 and 11.

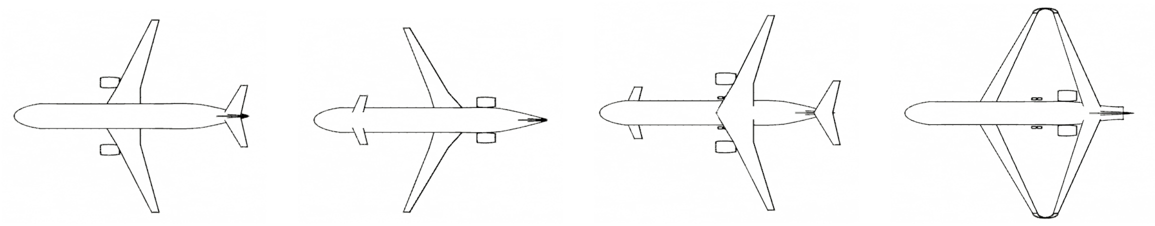
The conventional configuration designed by the *Initiator* is the baseline (see Section 4) to which the other configurations are compared.

Table 5 shows the percentage difference between the unconventional configurations and the conventional airplane designed for the same TLRs.

The *Initiator* is also used in the EC RECREATE project to support the design of a passenger airplane designed for air-to-air refueling (the *cruiser*) [22]. The *cruiser* is an airplane with a conventional configuration, but because of the high-payload combined with small range requirements it features a twin-aisle fuselage combined with a relatively small wing. As a consequence the fuselage needs to be able to withstand the loads introduced over the relatively small root chord length of the wing. While the impact of this higher load on the weight of the fuselage would not be visible using a classical Class II method, the Class II.V methods implemented in the *Initiator* allow to capture this effect.

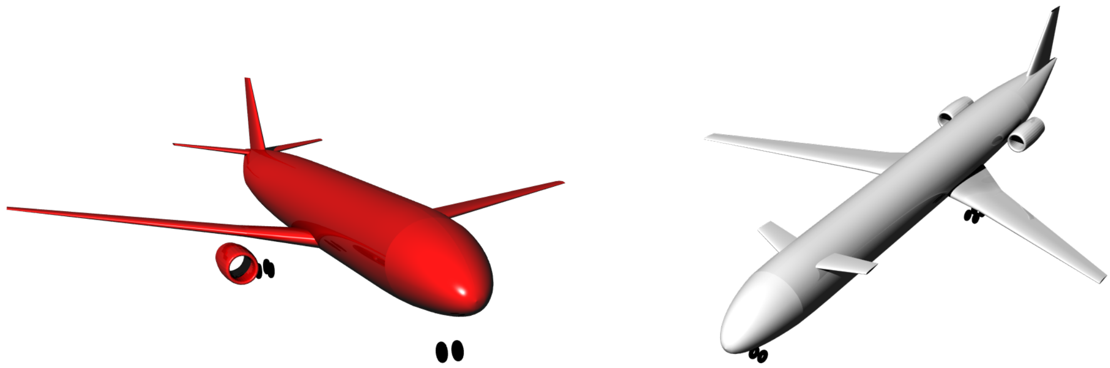
6 Conclusions and outlook

A design and analysis method has been integrated in a software framework, the *Initiator*, to compare new and unconventional configurations to the traditional tube-and-wing configuration. Examples have demonstrated the variety of configurations that can be designed and analyzed using uniform analysis tools. The inclusion of more physics-based methods enable the

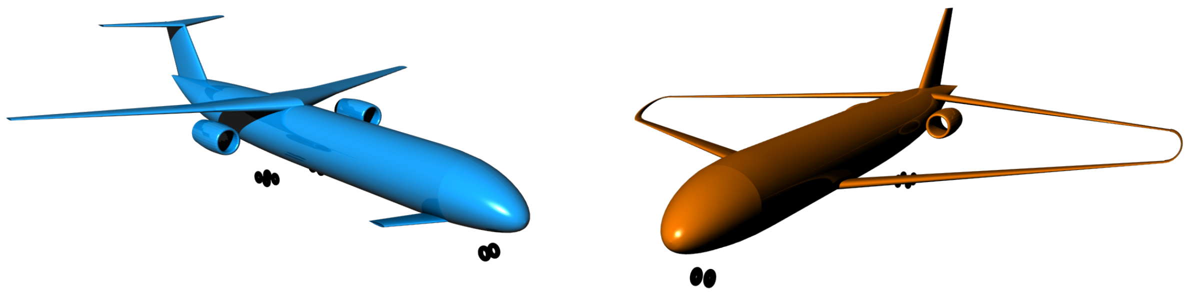


(a) Conventional (b) Canard (c) Three-surface (d) Prandtl

Fig. 10 Top views of the airplanes designed for a given set of TLRs.



(a) Conventional configuration (b) Canard configuration



(c) Three-surface configuration (d) Prandtl configuration

Fig. 11 3D-views of the designed airplanes

design and analysis of unconventional configurations and airplanes with unconventional requirements. The results presented in Section 5 are the result of the sizing rules implemented in the design tool. The designs all have different static margins and the designs are not optimized for a certain figure of merit. More advanced sizing rules for the wing and tail surfaces based on stability and control analyses and optimization of (for example) the longitudinal wing location may improve the design of the different configurations. Sizing rules for the Blended-Wing-Body airplane are under development. In order to address the design of non-conventional airplane an optimization method can be used to handle the design parameters and coupling between disciplines. This optimization module is currently under development and will be based on work done on previous design tools.

Acknowledgments

The development of the *Initiator* has been a group effort. Many graduate students have been contributing to the present design tool. The authors would like to acknowledge the valuable contributions of the following individuals: Mr.

Table 5 Comparison of the KPIs with respect to the conventional airplane

	Canard	TSA	Prandtl
W/S	-0.5%	+1.9%	-9.3%
T/W	-0.4%	+13.7%	-6.0%
L/D	+7.0%	-17.4%	-7.0%
MTOW	-8.1%	+8.1%	+24.5%
OEW	-11.5%	+7.8%	+36.1%
Fuel	-12.2%	+23.4%	+32.6%
C_{D_0}	-2.0%	+10.7%	+26.5%
e	+14.5%	-24.8%	+30.2%
DOC	-0.8%	+12.0%	+13.4%

Jorrit van Dommelen and Mr. Tom Langen for prototyping the baseline architecture of the tool; Mr. Maurice Hoogreef, Mr. Kristian Schmidt, and Dr. Ali Elham for developing new weight estimation methods for fuselage and wing, respectively; Mr. Niels Heerens for the implementation of the landing-gear sizing tool; Mr. Arne Slingerland for developing a generic tool for preliminary sizing; Mr. Jan Mariens for implementing high-lift analysis methods and Mr. Fulco Vaessen for developing an extension to the vortex-lattice method. The authors also would like the RECREATE project for enabling the development of this design tool. Furthermore, the authors would like to thank professor Egbert Torenbeek for providing advise during the course of this project.

References

[1] G. La Rocca and M. J. L. van Tooren. Enabling distributed multi-disciplinary design of complex products: a knowledge based engineering approach. *Journal of Design Research*, 5:333–352, 2007.

[2] G. La Rocca. *Knowledge based engineering techniques to support aircraft design and optimization*. PhD thesis, Delft University of Technology, 2011.

[3] G. La Rocca, T. Langen, and Y. Brouwers. The design and engineering engine. towards a modular system for collaborative aircraft design. In *Proceedings of ICAS 2012*, Brisbane, AU, September 2012.

[4] J. van Dommelen and R. Vos. Conceptual design and analysis of blended-wing-body aircraft. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, January 2014.

[5] R. Vos, F Geuskens, and M.F.M. Hoogreef. A new structural design concept for blended wing body cabins. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Sheraton Waikiki, Honolulu, Hawaii, April 2012. American Institute of Aeronautics and Astronautics, AIAA 2012-1998.

[6] B. Nagel, D. Bohnke, V. Gollnick, P. Schmollgruber, J. J. Alonso, A. Rizzi, and G. La Rocca. Communication in aircraft design: Can we establish a common language. In *Proceedings of ICAS 2012*, Brisbane, AU, September 2012.

[7] A. Elham, G. La Rocca, and M. Van Tooren. Development and implementation of an advanced, design-sensitive method for wing weight estimation. *Aerospace Science and Technology*, pages 100–113, January 2013.

[8] E. Torenbeek. *Advanced Aircraft Design: Conceptual Design*. Wiley, 2013.

[9] D. P. Raymer. *Aircraft design: a conceptual approach*. American Institute of Aeronautics and Astronautics, 370 L'Enfant Promenade, S.W., Washington, D.C. 20024, second edition, 1992.

[10] E. Torenbeek. *Development and Application of a Comprehensive, Designsensitive Weight Prediction Method for Wing Structures of Transport Category Aircraft*. Report LR-693. Delft University of Technology, Delft (Netherlands), September 1992.

[11] K. Schmidt and R. Vos. A semi-analytical weight estimation method for oval fuselages in conventional and novel aircraft. In *52nd Aerospace Sciences Meeting*. AIAA 2014-0026, January 2014.

[12] M. Hoogreef and R. Vos. The oval fuselage; a new structural design concept for blended-wing-body cabins. In *Proceedings of RAeS 3rd Aircraft Structural Design Conference*. Royal Aeronautical Society, 2012.

[13] K.M.C De Cock and R.K. Nangia. Research on a cruiser enabled air transport environment (recreate). In *RTO Workshop on Energy Efficient Air Vehicle Configurations and Concepts*

of Operation (Applied Vehicle Technology Panel AVT-209), Lisboa, Portugal, September 2012.

[14] J. Roskam. *Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics*. Roskam aviation and engineering corporation, 1990.

[15] Anonymous. 89034: The maximum lift coefficient of plain wings at subsonic speeds. Technical report, ESDU, 1993.

[16] K. G. Tang, A. G. Rao, and J. P. van Buijtenen. Conceptual study of a hybrid turbofan engine with inter turbine burner. In *ASME Turbo Expo 2010: Power for Land, Sea, and Air*, pages 239–248, Glasgow, Scotland, June 2010. American Society of Mechanical Engineers.

[17] J. Roskam. *Airplane Design Part VIII: Airplane Cost Estimation Design Development and Manufacturing and Operating*. Roskam aviation and engineering corporation, 1990.

[18] M. N. Beltramo. Beyond parametrics: The role of subjectivity in cost models. *Engineering Costs and Production Economics*, 14(2):131–136, 1988. Cited By (since 1996):7.

[19] D. V. Maddalon, J. K. Molloy, and M. J Neubawer. Computer programs for estimating civil aircraft economics. In *NASA Technical Library*. NASA, 1980.

[20] Élodie Roux. *Avions civils à réaction: plan 3 vues et données caractéristiques*. Elodie Roux, 2007.

[21] E Obert. Drag polars of nineteen jet transport aircraft at Mach numbers M = 0.40 - 0.60 (unpublished). Technical report, 2013.

[22] G. La Rocca, M. Li, P.P.M van der Linden, and R.J.M. Elmendorp. Conceptual design of a passenger aircraft for aerial refueling operations: A comparative study with direct and staging flight. In *Proceedings of ICAS 2014*, 2014.

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