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A discussion on benchmarking unconventional configurations with conventional aircraft: the box-wing study case

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Abstract

This article is intended to introduce an alternative approach to comparative analyses between innovative aeronautical technologies and established state-of-the-art references. Commonly, the tendency is to use a ‘like-for-like’ comparative approach with respect to current technologies -defined as reference benchmarks- that is, to evaluate the possible incremental improvements that can be achieved by introducing a specific technological innovation. However, when innovations that potentially introduce step improvements or new functions compared to the state of the art are evaluated, typically referred to as ‘breakthrough’, this approach may not be the most formally sound one, and it may introduce bias and misjudgements. In the field of aircraft design, using the same top-level requirements and figures of merit as those used for conventional aircraft to initialise and steer the design of unconventional configurations, could undermine the exploitation of their operating and functional potential. The soundness of the comparative approach is of paramount importance, especially in the very early stages of the development of disruptive technologies and unconventional aircraft configurations. In this paper, with the supporting example of the application of the box-wing configuration to medium-range transport aircraft, a general discussion is offered on the necessity of leaving aside the ‘like-for-like’ benchmark approach when investigating the potential of disruptive aircraft innovations. This argumentation does not only refer to the case study proposed as an example, but is generally extendable to aeronautical innovations that may introduce operating and functional novelties compared to current technologies.

Keywords Unconventional configurations · Aircraft design · Innovation · Benchmarking · Box-wing · Breakthrough technology

1 Introduction

The progress of transport aviation is at the beginning of a very significant transformative process. Increasingly pressing requirements regarding the mitigation of environmental impact, in terms of reduction of pollutant and greenhouse gas emissions [1–5], together with an increasingly growing demand [6], is driving research towards the study of more and more advanced solutions that could depart from the traditional ones [7]. Among these, innovative propulsion systems, such as electric [8, 9], hybrid-electric [10, 11] and hydrogen propulsion [12, 13], are of great interest. Several studies are also dedicated to advanced propulsion-airframe integrations and their

potential performance advantages [14]; these include boundary layer ingestion engines [15, 16] and distributed propulsion [17, 18]. Advanced and innovative solutions are also proposed and studied in the area of structures and materials [19, 20], as well as in the field of aerodynamic solutions [21, 22]. Finally, there are a large number of studies related to investigations into unconventional lifting configurations [23, 24], which differ partially or completely from the traditional tube-and-wing configuration, which is well consolidated for the air transport segment. Among these innovative architectures, we can mention the box-wing [25, 26], the blended-wing-body [27, 28], and the truss-braced wing [29, 30] configurations. In general, each of these technological and architectural innovations is proposed as an improvement to the current scenario. In some cases, the technological innovation is proposed as evolutionary of the state of the art, and thus providing an incremental contribute to one or more specific performances; on the other hand, some innovations intend to introduce performance or operating step changes, well beyond the capabilities at the state

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of the art. To properly assess the potential impact of such disruptive innovations on the current status quo, it is necessary and worthwhile to carry out comparative analyses with current technologies starting from the early stages of the conceptual investigation.

In this paper, it is, therefore, intended to provide a discussion on how to manage the initialisation of the design and the related performance comparative assessment of disruptive aeronautical technologies with respect to technology benchmarks. Specifically, as a general example, unconventional lifting configurations are taken into consideration and the focus is given to how the selection of state-of-the-art benchmarks, usually motivated by the need to maintain a certain unbiased in comparative analyses, could instead misdirect the development of the proposed innovations. The work presented in this paper, therefore, is intended to be of a very general purpose and is aimed at presenting an argued discussion on how in some cases it is necessary to vary the paradigm of conception, the choice of requirements, the development and performance analysis when dealing with disruptive concepts. As it will be addressed in the paper, in cases where the novelty introduced by the technological innovation is not of incremental character (e.g. an improvement in fuel efficiency) but instead introduces new functions not available in the state of the art, it is appropriate to loosen the like-for-like approaches with respect to current technologies. To support this discussion, the case of the box-wing (BW) configuration applied to medium-range transport aircraft is presented; the technical framework is limited to the conceptual design stage, which is however qualitatively sufficient to support the structure of the discussion. The example used only serves to argue the scientific rationale of the work; the latter, indeed, can be extended to several different breakthrough technological innovations.

The paper is structured as follows: Sect. 2 provides a wide overview of the context of conceptual design, its possible implementations, and its adaptation to innovative or unconventional aircraft; the issue of benchmarking with conventional configurations is also introduced. Section 3 presents the study-case used in this context, namely the box-wing aircraft; Sect. 4 briefly describes methods and tools used for the conceptual design and performance analysis. Section 5 gives the results of the different conceptual developments of the box-wing and of the comparative analysis with respect to the traditional competitor, while Sect. 6 provides a discussion of such results. Finally, conclusions are offered in Sect. 7.

2 The development of a new aircraft

2.1 Conceptual aircraft design

The aircraft conceptual design is the initial stage of the aeroplane development process; in this phase, the most relevant

architectural features and the related main expected performance are outlined. A new aircraft design plan is initialised when a significant improvement is to be achieved with respect to the state of the art, in terms of performance and operations; such performance requirements may be derived from specific customer demands and/or through the outputs of detailed market analyses [31]. These outputs can then be translated into design specifications, referred to as Top Level Aircraft Requirements (TLARs), which aim to steer and direct the entire design process [32–34]. The choice of TLARs has a huge impact on the entire design development [35, 36]; typical TLARs may be payload, range, cruise speed, airport constraints (e.g. runway length and apron compatibility), etc. During the conceptual phase, therefore, aircraft configurations that are capable to meet these requirements are qualitatively and quantitatively assessed, and their main characteristics are outlined, preliminary sketches are produced, key performance is estimated, and potential degrees of risk and related trade-offs are highlighted. Quantitative performance analyses are made by selecting proper Figures of Merit (FoMs); FoMs are functions/performance indicators that quantify how well a concept potentially performs with respect to the selected aircraft design objectives [37–40]; typical FoMs can be fuel consumption, pollutant emissions, operating costs. Maximising/minimising a specific FoM involves the need to act on the design variables and to identify trade-offs between these and the selected performance targets; hence, as for the TLARs, also the proper selection of FoMs has a key impact on the concept development [41]. Although typically based on simplified analysis tools of low-to-medium fidelity, and usually driven by the experience of the designers [42, 43], the conceptual design is the pivotal and fundamental phase of the entire aircraft development; errors at this level can dramatically affect time and costs in the more advanced stages of the design process. On the other hand, misleading estimates can lead to the discarding of configurations that can offer higher performance.

2.2 The basic requirement and the feasibility study

A broader view concerning the approach towards the design of a complex product such as the transport aircraft is provided by Ref. [44]; in this case, even before the definition of the detailed specification (TLARs) of the aircraft, a preliminary phase is introduced relating to the identification of the main functional tasks/requirements that the machine to be designed must satisfy; let us call this the ‘*basic requirement(s)*’. Subsequently, different configurations and architectural/technological solutions are evaluated in an extensive feasibility study, with the aim of verifying that the basic requirement addressing the design can be realistically verified by one or more of the assessed configurations;

a simplified schematization of this approach is proposed in Fig. 1.

Only after this phase, i.e. once the overall sets of key technological/architectural choices of the vehicle have been defined, the detailed requirements can be finalised, namely those that compose the list of TLARs. But how does it come to the need to define a basic requirement that justify the initialisation of a new design programme? In Ref. [44] this starts when the aviation industry needs to satisfy functional requirements that are not compatible with the capabilities of existing aircraft and/or because technological developments allow new functions to be explored. In both cases, therefore, it is possible that the basic requirement is completely novel compared to the functions of state-of-the-art aircraft. During the feasibility study phase, therefore, different possibilities are examined that can potentially satisfy the basic requirement; in general, it is possible to consider an upgrade of a state-of-the-art configuration (e.g. a new more efficient propulsive system, as for the case of the Airbus A320neo [45]), or to integrate innovative technological solutions that directly modify the airframe or propulsion of existing aircraft (e.g. hydrogen propulsion [13, 46]), or to design a completely novel configuration (e.g. the blended wing body [47, 48]). The latter option is undoubtedly the most high-risk one, especially in the aeronautical context, but it may also be the most suitable for the fulfilment of novel basic requirement(s). Decisions made in the feasibility analysis phase thus have extreme repercussions on the development of the whole project, and incorrect or unjustified assumptions can reverberate both on the actual fulfilment of the basic requirement and on the entire success of the project. In fact, as also remarked by Ref. [49], such choices are often made on the basis of experience or the intuitions of the design offices, or are based simply on the evolutionary development of established concepts; at this crucial stage, according to Ref. [49], such approaches could easily lead to the choice of underperforming configurations, or to the complete disregard of alternatives that are better but counterintuitive, as can easily occur with non-traditional configurations. An alternative that could limit such uncertainties during feasibility studies is to switch to systematic and structured methods capable of identifying potentials and showstoppers of the examined configurations with respect to the basic requirement. One such approach is the Quality Function Deployment [50–53], a systematic procedure

capable of correlating in the initial stages of the project the basic requirement with the different technical and architectural features possible to satisfy that requirement, by means of a functional assessment [54, 55].

In general, however, whatever the approach with which this feasibility analysis is carried out, its output is represented by the detailed design specification (i.e. TLARs) and the configurational options potentially adequate to satisfy it, to be evaluated in the subsequent conceptual design phase. To accomplish the latter, a decision-making phase is typically conducted; this involves the use of logic-based yes/no criteria to select or reject configurations for advancement to the next design phase. In the decision-making phase following a feasibility study, logic-based criteria are essential for ensuring a systematic and objective approach to selecting configurations for further development. By establishing clear yes–no criteria aligned with project objectives and feasibility constraints, decision-makers can effectively evaluate the merits of each configuration and make informed decisions.

2.3 Evolutionary against breakthrough approaches

As seen in Sect. 2.2, prior to the actual definition of the detailed project specification, one or more basic requirements should be identified to steer the architectural feasibility study. The choice of such requirement(s) may be driven by market developments that open up new opportunities, by needs arising from infrastructural bottlenecks, by new regulations not previously foreseen, by specific customer requirements, by the emergence of new technologies, and so on. In this context, we can qualitatively identify two different directions for the initialisation of a new aeronautical project; one, which we can define as ‘*evolutionary*’, which is aimed at the incremental improvement of the performance of state-of-the-art aircraft, and which therefore builds its foundation on the development and optimisation of already established technologies. In this scenario, the selection of architectures and technologies similar to more traditional ones is practically taken as a granted option, and an incremental refinement approach also represents the lowest risky one. Even the definition of the detailed specification, i.e. the TLARs, will not deviate much from those that have guided the development of state-of-the-art benchmarks.

In cases where the basic requirement(s), however, imposes conditions that presumably go far beyond the

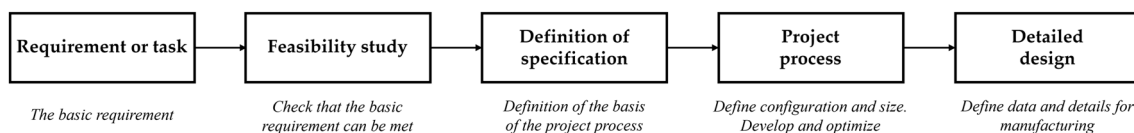


Fig. 1 General aircraft design process according to Ref. [44]

capabilities of canonical configurations, the evolutionary approach may fail to meet them, and a shift towards ‘*breakthrough*’ solutions may prove successful. In order to provide some historical qualitative examples (of the past, present, and future), a series of basic requirements that led to the introduction of disruptive solutions are proposed:

- Infrastructural showstoppers: apron size standards provided by ICAO [56], impose constraints on maximum wingspan; to improve the aerodynamic efficiency by increasing wing aspect ratio, and at the same time complying with ICAO ‘E’ aerodrome code standard, the Boeing 777X has two foldable wingtip (3,5 m each) [57]. These are extended in flight to increase wingspan, and are retracted during ground manoeuvres.
- Opportunities from new markets: the development of the novel Urban Air Mobility market, involving urban short-range low payload point-to-point aerial transportation, boosted the research and development of disruptive electric vertical take-off and landing vehicles, see Ref. [58–60].
- New policies and regulations: the ambitious net-zero emissions plan provided by European policymakers, steered the development of disruptive propulsive concepts, as for example the hydrogen-powered transport aircraft [12].
- Specific customers requirement: to meet the demand for supersonic civil air transport, showcasing technological superiority and national prestige, steered the development and the introduction in the market of the supersonic airliner Concorde [61].
- Emergence of new technology (past): the achievement of the technological maturity and the required reliability of turbojet engines enabled the design and entry into service of the first jet airliner, the de Havilland Comet [62].
- Emergence of new technology (future): the growing technological maturity of electric power generation and energy storage systems is driving the extensive study and development of electric and hybrid-electric aircraft, especially in general and regional aviation [8–10].

Therefore, breakthrough configurations must be taken into account especially if their inherent innovative features fit basic requirement(s), which can hardly be fulfilled by evolutionary approaches.

As mentioned in Sect. 2.2, having defined the basic requirement(s), the outcomes of the feasibility analysis are mainly the identification of the architectural and technological choices to satisfy these requirements, and the definition of the detailed specification (TLARs). If in the evolutionary development approach, TLARs could reflect those related to traditional concepts, in the case of disruptive developments these may differ from the latter, even by a large margin. In

this scenario, therefore, a major issue emerges in assessing the effectiveness of introducing non-conventional aircraft: if the design specifications are different from those guiding the development of conventional aircraft, how should a reference benchmark be appropriately selected to assess comparative studies, and which figures of merit should be used?

2.4 The problem of benchmarking

The need for established, reliable, fair, and credible comparisons is of paramount importance in assessing the performance and operating potential of a novel aircraft. In the literature, the common approach is to perform direct, ‘*like-for-like*’ (or ‘*apples-to-apples*’, as it is usually said) comparisons. This approach is totally appropriate in the case of evolutionary aircraft development, as it is capable of bringing out in a quantitatively direct manner the potential performance gains or disadvantages that can be achieved. In the wake of established evolutionary studies, which have led to the optimised development of the current subsonic transport aircraft configuration having the tube-and-wing (TW) architecture, like-for-like comparisons are therefore considered as a necessary tool to evaluate new configurations in a credible and fair manner. This often led to the design of aircraft, even non-evolutionary but disruptive ones, starting from the same TLARs as traditional configurations. Some examples can be found in Ref. [63, 64] for the electric or hybrid-electric aircraft case, or in Ref. [28] for the blended-wing-body configuration, or box-wing configurations in Refs. [65, 66]. The definition of the basic requirement and the carrying out of the feasibility analysis as described in Sect. 2.2, is then entirely skipped, and the set of TLARs is fixed a priori on the basis of the current scenario, to retain like-for-like assessments. In several cases, this could imply a misleading initialisation of the aircraft design, especially for very innovative architectures. In fact, it should be emphasised that the comparative and benchmarking activities of very complex products such as transport aircraft, especially if unconventional, is a subject that can hide pitfalls and challenges that must be tackled with accuracy. Selecting TLARs identical to conventional aircraft for the only purpose of maintaining the like-for-like philosophy may result in potential ambiguity and skewed conclusions. Provocatively, it may be asked what conventional benchmark the Concorde was to be compared with during its initial design studies. The operating function introduced by such a non-evolutionary concept, i.e. commercial supersonic flight, could not meet any of the established state-of-the-art requirements; on the other hand, using benchmark-based figures of merit, i.e. fuel consumption, would certainly have undermined its development. To avoid such biased scenarios, it might be appropriate to loosen the rigidity of ‘*apples-to-apples*’ approach, and rigorously identify specific functional comparative analyses that can bring

out the inherent operating potentials of the disruptive innovations investigated. In general, disruptive innovations could introduce completely new evaluation standards: maintaining traditional performance metrics may not contemplate industry-transformative scenarios. For example, if a disruptive aircraft design emphasizes reducing environmental impact, only comparing it to traditional aircraft optimizing on cost or profitability could undermine its much larger environmental contribution. Hence, the philosophy that correlates the only possible fairness to like-for-like approaches might inherently prove contradictory, as it might (even unintentionally) overlook the transformative potential inherent in disruptive concepts. This paper aims to provide a reasoned discussion specifically in this context.

3 The box-wing study case

3.1 Box-wing features

To present an effective and functional study case to support the discussion presented in this paper, the box-wing configuration was selected as an unconventional reference. This configuration consists of a biplane lifting system, whose two main horizontal wings are joined at the wingtips by

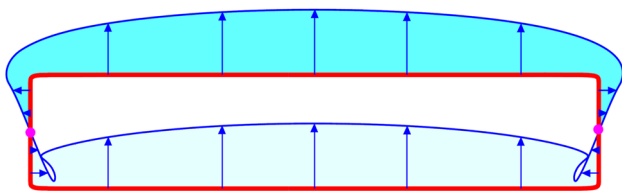


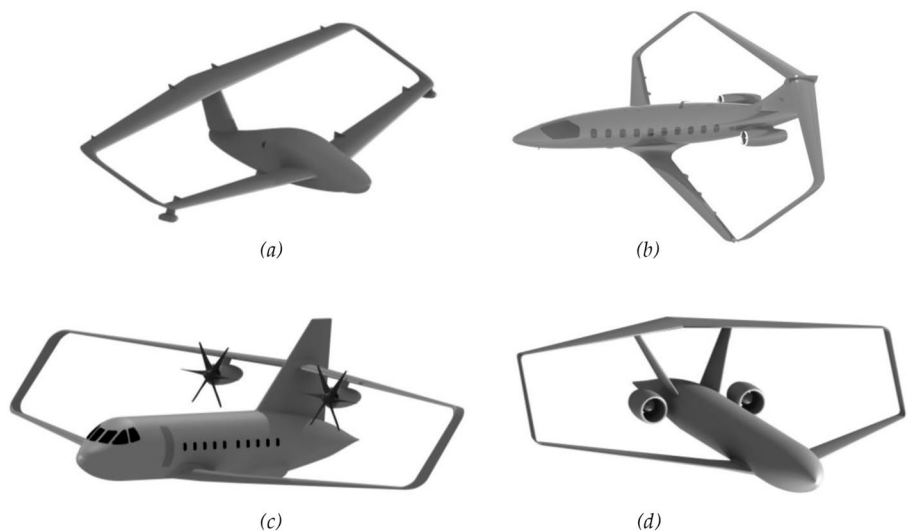
Fig. 2 Best Wing System optimum lift distribution. Image adapted from [24]

two properly sized vertical wings. This concept has been introduced since the very beginnings of aviation, thanks to the early prototype proposed by the pioneer Alberto Santos Dumont [67]. Such a lifting system was then identified by Prandtl as the one capable of minimizing induced drag among all the systems with equal wingspan and equal lift [68], and was named the ‘best wing system’; the optimal lift consists of an elliptical distribution plus a constant contribution on the main wings, and a butterfly-shaped contribution on the vertical tip-wings, as sketched in Fig. 2. Several solutions have been proposed in the literature, see Refs. [69–74], and also some small aircraft have been studied (see Refs. [75, 76]) and manufactured, cf. Refs. [77, 78]. Prandtl’s assumption was later proved in Ref. [79], and several studies on optimal lift distribution were proposed in Refs. [80–82].

The transfer of this theoretical concept to aeronautical engineering applications has led to different configurational proposals for transport aircraft [83, 84], as shown in Fig. 3; in honour of Prandtl, such a configuration is often referred to as *PrandtlPlane*.

Potential advantages of such a configuration include a possible improved aerodynamic performance, achievable through minimizing induced drag, and an increased potential to generate lift for the same wingspan as a traditional architecture aircraft, due to the presence of two main lifting wings. However, there are also still a number of uncertainties associated with the development of this concept, mainly related to the need to further explore aeroelastic features and certification issues. There can be two ways of exploiting such a concept, as outlined in Sect. 5: using it in an evolutionary view, thus as an incremental improvement to the state of the art, or in a breakthrough view, thus going beyond the state of the art with the aim of exploiting the technological leap to meet a basic requirement otherwise unlikely attainable with traditional architectural solutions. Thus, in the first case, a

Fig. 3 Applications of box-wing architecture to different aircraft categories: **a** seaplane [85], **b** commuter [86], **c** regional [87], **d** medium-range airliner [88]



like-for-like design and benchmarking approach is chosen, in which the design requirements (TLARs) are set equal to those of the best conventional competitor, and performance comparisons are made through the canonical FoMs for which the canonical competitor has been largely optimized. Specifically, a non-conventional configuration is thus introduced without the purpose of fulfilling any additional basic requirements compared to the established transport aviation sector. In the case at hand, this means simply replacing a wing-tail system with a box-wing system, keeping the ‘aircraft system’ virtually unchanged, and attempting to exploit only the potential aerodynamic and structural benefits arising from the peculiarity of the lifting system. In the case of the breakthrough design scenario, on the other hand, the non-conventional configuration is selected because it could fulfil a basic requirement not potentially achievable with traditional architectures. Therefore, the like-for-like approach can no longer be valid, and there is a need to develop such a configuration with a set of TLARs specifically tailored to the new basic requirement and to the performance and functional capabilities peculiar to the technological innovation being investigated.

The choice of the box-wing configuration as the subject of this discussion is based on the authors’ experience in its design, development, and analysis. Such experience, in fact, expressed through different studies related to aerodynamics [89, 90], flight mechanics [91, 92], structures [87, 93], and design and performance analysis [94, 95] allows the discussion to be argued in a sound and well-founded way. However, the discussion presented in the paper is of a general purpose and could be valid for any unconventional configuration that proposes to satisfy a basic requirement potentially not achievable by the incremental evolution of traditional architectures.

3.2 Box-wing literature analysis

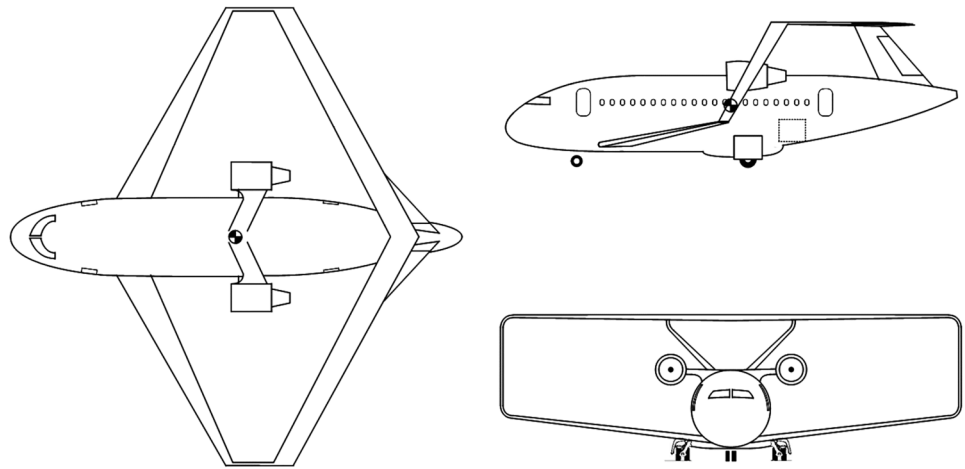
There are several conceptual studies in the literature related to the design of box-wing transport aircraft. Most of these are all related by the same common thread: the need to design the box-wing aircraft starting from the same top-level requirements as a conventional aircraft taken as a benchmark. This assumption has thus been interpreted in different ways by the different authors who have dealt with the subject. In Ref. [65], a multidisciplinary early sizing study of a medium-range box-wing aircraft is presented; this study is considered in the literature to be among the early key references regarding the conceptual design of BW aircraft. Although the tools used are of low fidelity, the study intends to holistically include all aspects characterizing the design of the aircraft, from aerodynamics to structural weight, from stability to propulsion, and finally to performance analysis. The design is initialized with a set of very strict assumptions:

(i) the need to set the same design requirements as the conventional benchmark, i.e. the Airbus A320; (ii) claiming to ensure a clear comparison, the TW and BW must have the same wingspan and the same wing area; (iii) the two main horizontal wings of the BW must have the same surface area. Point (i) is exactly the subject of the discussion presented in this paper; point (ii), though, seems extremely restrictive, as it unequivocally directs the design of a non-conventional architecture, with only the need to keep ‘everything equal’ to the benchmark; finally, point (iii) remains quite unjustified. As a result, these lead to an aircraft that, although it exhibits an estimated 9% reduction in fuel consumption, it also has a series of architectural drawbacks that would undermine its actual feasibility: the individual wings are extremely slender, with an estimated AR of 19 (see Fig. 4); even if an aerodynamic benefit is introduced in terms of reduced induced drag, the AR value is significantly higher than the state of the art bounds, and it is reasonable to expect huge increases in structural mass. Furthermore, no aeroelastic considerations are made that would reasonably compromise the feasibility of such a lifting system. The wing tank turns out to be about half that of the TW competitor; this is not intrinsic to the BW configuration but is merely due to the severe assumptions on wing surfaces. This design choice also implies design corrections aimed at longitudinal static stability, which substantially influences the fuselage design and engine positioning. However, as demonstrated in Ref. [91], keeping a constraint that forces the surfaces of the two wings of the BW to be equal is not only unnecessary but may prevent the stability and longitudinal control of the BW aircraft. Furthermore, in this approach of a comparison that must stringently maintain the same TLARs and the same wing surfaces and span of the benchmark, it is unclear why the fuselage is free to be completely different from the reference (short fuselage and twin-aisle cabin in this case).

In quantitative terms, the presented performance of such a concept may be arguable, given the fidelity level of the analysis models used, but in general results are clear that the architectural disadvantages of the BW sized according to these criteria are such that they likely undermine its chances of further development.

Also in the work presented in Ref. [66], a like-for-like approach is used for the conceptual comparative analysis of a box-wing transport aircraft and to identify possible incremental improvements. In particular, the same TLARs are used to size both the box-wing aircraft and the conventional benchmark, belonging to the regional jet category. In addition, certain geometric parameters are also set equal between the two configurations, to allow an ‘*effective comparison*’ (quote); among these, it is decided a priori that the reference surface of the two lifting systems must be the same. As mentioned above, these forced constraints inserted to maintain a certain unbiasing in the comparative study have

Fig. 4 Three views of the box-wing proposed in Refs. [65, 96]



a decisive impact on the design development, introducing penalties or compromising specific design aspects. In the case of Ref. [66], for example, the choice of the equivalence of the reference surfaces is justified by the fact that this parameter governs take-off performance, which is thus kept the same for the two compared configurations. This, however, is a significant flaw, as the low speed and take-off performance of a box-wing configuration does not depend on the total wing loading (i.e. W/S , where S is the reference surface including both wings). As shown in Refs. [91, 97], instead, such performance depends on the wing loading of each individual wing, defined as the ratio between the lift generated by the given wing in the considered operating condition and its surface area, i.e. L_{fw}/S_{fw} and L_{rw}/S_{rw} for the front and rear wing, respectively. In the end, albeit with low-to-medium fidelity models, an incremental improvement for the box wing in fuel consumption over the benchmark of 5.2% is identified in Ref. [66].

A similar approach is proposed in Ref. [98], where the need to maintain the same TLARs between the TW and BW configurations compared is kept, considering a 270 passenger aircraft for a 4000 nm design range; in this case, however, both the constraints on equal wing area and equal wingspan between the TW and the BW are relaxed. This makes it possible to design a BW with two lifting surfaces that individually have an aspect ratio comparable to that of

the TW, and with architectural choices that do not generally imply critical issues in the feasibility of the aircraft. A comparison of the configurations proposed in Ref. [98] is depicted in Fig. 5.

In the work proposed in Ref. [99] the comparative assessment is made between BW and conventional reference starting from the same TLARs, once again with the explicit aim of keeping unbiased the comparison; in this case regional jets with 86 passengers and a 1540 nm range are considered. The approach used is based on constrained multidisciplinary design and optimisation (MDO) to carry out the conceptual design of the configurations; the constraints refer to some basic aspects related to static stability, trim, performance (e.g. in take-off), and the available volume for the fuel tanks, which are considered to be installed only inside the wings. The MDO results show that the BW configuration, although having a slightly better performance in aerodynamic terms (+6.2% in lift-to-drag ratio L/D), exhibits a worsening in terms of fuel consumption of about 2%. This result is related, according to the authors of Ref. [99], to the need to increase the total reference surface area of the BW lifting system, that is +51% larger than the conventional benchmark; this huge increase, considering that the aircraft are designed for the same TLARs, is related to the only purpose of designing a wing tank compatible with the fuel volume required. Correspondingly, there is also a detrimental effect on take-off

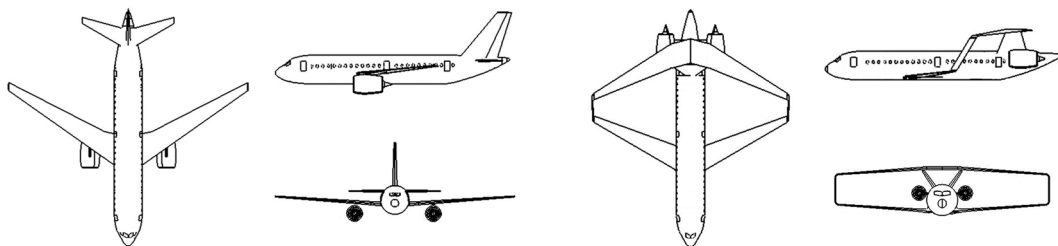


Fig. 5 Three-view comparison of the TW and BW aircraft proposed in [98]

weight, which is 9% higher for the BW. In this case of Ref. [99], therefore, to maintain an approach considered unbiased for the development of the conventional configuration, there is a forcing of the design of a fundamental aircraft component such as the wing to a secondary requirement (tank volume); this, in practice, could be relaxed through other design choices, i.e. additional tanks in the fuselage, or variation of TLARs. The definition of the wing area, in the conceptual sizing of an aircraft, must certainly ensure an adequate internal volume to accommodate the fuel tanks, but it must be optimised in view of the aircraft's high and low-speed performance. Hence, maintaining fixed requirements and constraints for the two configurations to keep the comparison unbiased, actually has the opposite effect of distorting the design development of the non-conventional configuration.

In Ref. [100], higher fidelity numerical methods were used to assess the aerodynamic performance of the box wing, with the aim of using this information to make a preliminary assessment of fuel consumption and to compare it with a conventional benchmark. Also in this case, the approach used is to design innovation to provide incremental performance gains, with the selection of TLARs in a like-for-like view of the conventional competitor; the TLARs are chosen starting from those of the Embraer E190 aircraft operating in the regional jet sector, i.e. 100 passengers for a design range of 500 nm and a cruise Mach of 0.78. In this case, however, no a priori conditions are set on the reference surface S_{ref} or its front/rear distribution, but the wing surface is designed by means of an optimisation procedure. This procedure, based on RANS aerodynamic solvers, adopts the aerodynamic shape optimisation technique; the object of the optimisation is only the lifting system, while the fuselage and the tailplanes are omitted from the RANS calculation for both configurations. The wingspan is instead set equal between the two configurations; wingspan can however be considered effectively as one of the TLARs, as this parameter is constrained by compatibility with ICAO-standardised airport aprons [56]. Another assumption made is the equality of MTOW between box-wing and tube-and-wing, with a sensitivity range of $\pm 5\%$. The results obtained for the optimised configurations are shown in Table 1, while the planforms of the optimised lifting systems are depicted in Fig. 6.

The results show a reduction in fuel consumption that can reasonably be estimated between 4 and 9% for the BW. Although the aerodynamic analyses are accurate and reliable, and the comparisons in terms of aerodynamic coefficients are soundly based, the fuel consumption estimates and performance conclusions are rather uncertain, since: (i) having the same TLARs has resulted in the design of individual box-wing lifting surfaces with very high wing aspect ratio: this may reasonably compromise structural weight estimations and/or introduce feasibility issues with respect

Table 1 TW and BW comparative results. Data taken from Ref. [100]

Configuration	Weight [kg]	S_{ref} [m ²]	L/D	$\Delta\%$ fuel
TW	41,460	93	16.4	Ref
BW (-5%)	39,390	111	17.2	-9.1
BW	41,460	112	17.9	-7.2
BW (+5%)	43,530	113	18.4	-4.8

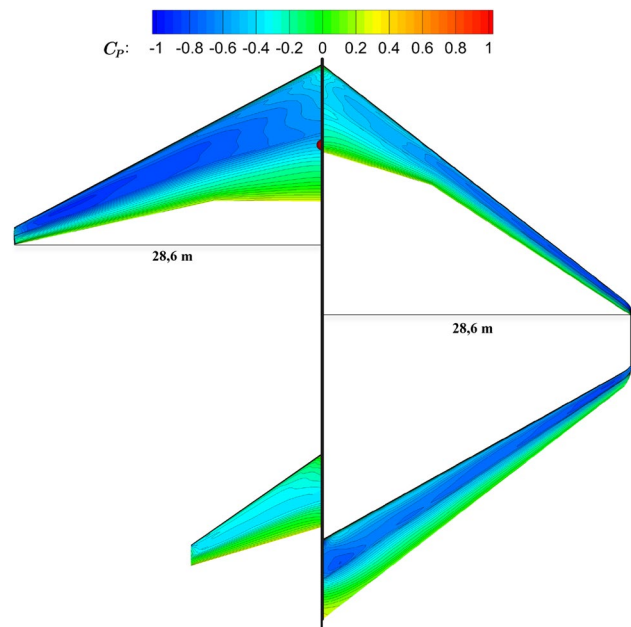


Fig. 6 Pressure coefficient contour maps for the optimized planforms. Image adapted from [100]

to aeroelastic design; (ii) the weight and fuel consumption assessment models are of low-fidelity; (iii) only the lifting system is simulated, while the effects of the fuselage, fairings, empennages, and related interference are assessed with approximate methods. Point (i), however, is the one that, in a decision-making process, could have the highest relevance in discarding the configuration during a feasibility analysis.

4 Methodology

4.1 Initial sizing

This section describes the models and the methodologies employed in the initial stages of the investigation discussed in this paper. Specifically, in the early phases of the aeronautical design, it is useful to use rapid models although reliable in capturing the main correlations between the figures of merit steering the design and the variables defining the engineering problem. In this way, it

is possible to evaluate a large number of configurations in a limited amount of time, and thus to determine the main architectural and configurational choices that characterise the subsequent detailed development of the design process. In the context of this paper, the design scheme proposed in Fig. 7 was adopted to address the conceptual phase of the aircraft design and thus collect useful data for the qualitative understanding of the features of the investigated concepts. A detailed description of the procedure is provided in Ref. [94], hence in the following a general overview is given; the procedure applies for both the box-wing and the tube-and-wing.

Specifically, the design flow is initialized by providing a set of main TLARs, such as design range, number of passengers, cruise Mach, etc. Thus, the initial mass breakdown of the aircraft is calculated by some ‘Level 0’ methods, i.e. statistical or semi-empirical relationships available in the technical literature. In this case, the well-established models for aircraft conceptual assessments proposed in Refs. [101–103] have been adopted. These models have been slightly adapted to also apply to box-wing lifting systems, namely adding the weight of the vertical tip-wings and the double vertical tail assembly. In the following phase, an optimization-driven design of the lifting system is performed by means of the in-house software called AEROSTATE; this code, extensively described in Refs. [104, 105], solves the constrained aerodynamic optimization problem proposed in Eq. (1):

$$\begin{cases} \min \left(-\frac{L}{D}(x) \right) \\ W - \varepsilon \leq L(x) \leq W + \varepsilon \\ S_{M \min} \leq S_M(x) \leq S_{M \max} \\ \varepsilon_M \leq C_M(x) \leq \varepsilon_M \\ (L/S)_{\min} \leq (L/S(x))_{fw} \leq (L/S)_{\max} \\ (L/S)_{\min} \leq (L/S(x))_{rw} \leq (L/S)_{\max} \\ lb < x < ub \end{cases} \quad (1)$$

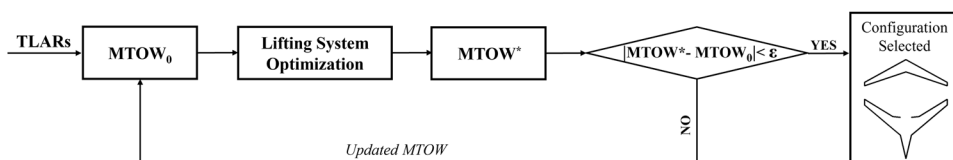
The objective function to be maximized is set as equal to the lift-to-drag ratio L/D at the beginning of the cruise phase; the main constraints are related to the cruise trim and stability. Specifically, lift L must equilibrate the cruise weight W , the static stability margin S_M must be positive and within a prescribed interval, and the pitch moment

coefficient must C_M be zero without considering any elevator deflection. User-specified tolerances ε as well as other further constraints can be added to the optimization problem (e.g. constraints on maximum and minimum wing loading L/S for the front wing fw and rear wing/tail rw). The aerodynamic solver used to compute induced drag and stability aerodynamic derivatives is the vortex lattice method AVL [106]. Parasitic drag of the lifting surfaces is computed by integrating over the wing surface the airfoil CD_0 computed by XFOIL [107], whereas fuselage, pylon, nacelles parasitic drag and interference drag are assessed by the methods proposed in Ref. [101]; finally, the possible wave drag is computed by means of the Korn-Lock-Mason simplified formula [108]. The design variables vector x contains any variable defining the wing system geometry, as reference sections chords, twist angles, x, y, z positions of their leading edge, and reference bays sweep angles, taper ratio, and dihedral angles. The x vector is bounded by the designer within the design space identified by the lower and upper boundaries, lb and ub , respectively. The optimization algorithm combines global and local minima search methods, as detailed in Refs. [109].

4.2 Refined performance assessment

To provide quantitatively more accurate performance estimations, on the other hand, it is necessary to use more advanced simulation models than those described in the previous section. Typically, such tools require more effort in the model preparation and significantly higher computational capacity and times. For this reason, their application is usually not compatible with the typical requirements of the very early design phase, in which a large number of configurations need to be evaluated in a reasonably short time. Rather, advanced simulation models are used in subsequent design phases to better characterise aircraft performance and possibly identify any potential corrective design measure. A similar approach was used in this comparative study. Specifically, regarding aerodynamics, CFD simulation models based on steady and compressible RANS solvers, with a $k-\varepsilon$ turbulence model, were used to compute the aerodynamic polar curves in different operating conditions; more details on the CFD aerodynamic modelling used in this work can be found in Refs. [90, 94]. Numerical simulation models were also used for the sizing of the primary structures of fuselage and lifting surfaces; in particular, FEM-based models were used considering only

Fig. 7 Conceptual sizing general scheme



static loading conditions, taking the cruise starting point as the reference operating condition. Details on the FEM-based structural sizing methodology are discussed in Refs. [93, 94]. The main outputs of this model are the structural masses of wings and fuselage. The new updated information on aircraft aerodynamics and weights can then be input into a mission simulation tool, specifically in-house developed to assess the performance of the designed configurations, see Fig. 8.

This tool, by time-integrating the flight dynamics equations of the aircraft point-mass model in the longitudinal plane, allows to extract some relevant mission performance, as the block fuel consumed. This information is processed again by the ‘Level 0’ weight model in an iterative loop that ends when the maximum take-off weight reaches convergence. This conceptual framework is used in this paper to provide qualitative insights on the comparison between box-wing and tube-and-wing aircraft. In view of the degree of fidelity of the models adopted, rather than provide specific quantitative performance information, it is used to extract comparative remarks that can highlight the main differences between different configurations.

5 Results

5.1 Conceptual assessment

This section provides the results of comparative design between different box-wing and tube-and-wing aircraft configurations, obtained in the early stage of the design process. The tools used to design and analyse the aircraft are those described in Sect. 4.1, referring to the typical fast methods used in the conceptual phase. These allow to design several configurations, enabling the identification of main trends and correlations between performance and design variables and, in the case of comparing different architectures, of their macroscopic performance differences and similarities.

Nevertheless, due to the medium-to-low degree of fidelity of these tools, the outcomes of the comparisons are intended to be as qualitative indicators, and useful to understand possible functional, operating and performance main differences between the two concepts. Section 5.1.1 focuses on the comparative study based on the like-for-like approach, whereas Sect. 5.1.2 introduces a different way to develop the box wing following a specific-defined set of TLARs. The fundamental technological bricks, such as propulsive efficiency and specific fuel consumption, materials and structural assembly, airfoils aerodynamic performance, degree of development of systems, are considered equal for each configuration discussed in the following.

5.1.1 Aircraft design for the same TLARs

To kick-start the discussion on this comparison, a set of Top Level Aircraft Requirements identifying current jet-powered aircraft operating on medium routes, such as the Airbus A320 [110], is taken as a reference; the main target TLARs are provided in Table 2; the design drivers are the payload and range, the cruise operating conditions and the maximum wingspan. This latter requirement is of key relevance in steering the wing design, and it is strictly related to the infrastructural constraint regulating the airport apron compatibility. Specifically, aircraft belonging to the short-to-medium range category typically comply with the ICAO Aerodrome Code ‘C’ constraint, limiting the wingspan to 36 m.

The two lifting architectures are inherently different. It is not only the shape and the arrangement of the wings that is different, but also the functions allocated to them are substantially dissimilar; this considerably influences the design of the entire aircraft. As a relevant example, the case of static stability and trim in the longitudinal plane is considered: in general, the TW aircraft assigns the lifting functions to the main wing, while the stability and trim are provided

Fig. 8 Mission simulation general scheme

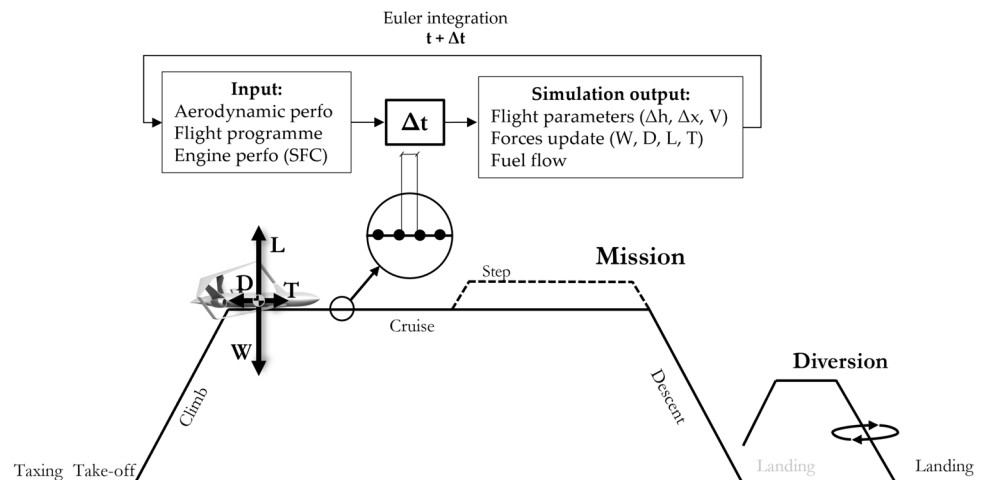


Table 2 Reference medium-range aircraft TLARs

Max n° of passengers	186
Harmonic range	5000 km
Cruise Mach	0.79
Initial cruise altitude	11,000 m
Max wingspan	36 m

through the integrated design of the horizontal tailplane. For the BW aircraft, on the other hand, this distinct separation of functions between the two horizontal lifting surfaces cannot be made, since both wings have the concurrent task of fulfilling vertical equilibrium and longitudinal static stability and trim. This affects the design of the lifting system, as aeromechanical and aerodynamic requirements cannot be separated. This problem has been extensively discussed in Ref. [91], in which it is stated that the constraints of static stability and longitudinal controllability significantly influence the design of the box-wing lifting system, mainly by impacting on the repartition of wing loadings between the front and rear wing; specifically, the front wing (hereafter also referred to as the BW ‘main’ wing) requires a higher wing loading, and the ratio of rear-to-front wing loading can assume values between 0.5 and 0.75. Hence, the design of the two horizontal wings is significantly coupled. Conversely, the wing and tail combination of the TW follows different a design path than the lifting system of the BW, and hence there is a need to find some common point in the early design choices to properly set a comparative study. For this reason, therefore, two different strategies for comparable conceptual design between BW and TW are proposed in the following; the design is initialized for both following the TLARs in Table 2, in the canonical like-for-like approach, as discussed in Sect. 2.3. The first strategy to compare the two configurations is to design aircraft with a comparable (a strict equality constraint would have introduced numerical issues unnecessarily at this stage) main wing loading $(L/S)_w$; the main wing is clearly defined for the TW, whereas it is selected as the front wing for the BW; this is a general convention, since, as said before, the design of front-rear wings of the BW are inherently intertwined. Both the lifting architectures have the same airfoil. The results obtained by applying the conceptual design procedure described in Sect. 4.1 are proposed in Table 3, which reports the values of the wings’ surfaces S_w (front/rear) and aspect ratio AR_w , the maximum take-off weight MTOW, the operating empty weight W_{oe} , the lifting system weight W_{wing} , the wings’ loading L/S , and the design point lift-to-drag ratio L/D . The lifting systems planforms are sketched in Fig. 9-left for the TW and in Fig. 9-centre for the BW; the latter configuration is renamed BW_1 . Following this approach, the BW_1 designed by means of AEROSTATE, hence following

the set of aeromechanical constraints listed in Eq. (1), has a total wing surface slightly larger than that of the main wing of the TW, but considering the split between the front and rear wings, the planform results in very slender individual wings; specifically, the front and the rear wing exhibit an aspect ratio of 14.7 and 17.8, respectively. These values are definitely far from the state of the art and could introduce severe penalizations in terms of structural weights up to the unfeasibility of the concept. By means of very simplified weight estimation models [102, 103], it is calculated that the wing structural weight and operating empty weight increases by 64.6% and 11.6%, respectively; see Table 3. This reflects on an MTOW that is + 7.2% larger. Furthermore, aeroelastic constraints, not quantitatively assessed in this phase, could likely prejudice the actual design and development of such a lifting system, due to the very high values of AR. Finally, similar problem on available tank volume to that found by [99] are likely to be expected. Therefore, since a yes/no choice has to be made in the decision-making phase at the end of the feasibility analysis (see Sect. 2.2), the answer could easily be ‘no’ without the need for additional investigations for this layout.

To overcome this potential showstopper for the further development of the BW, another design is proposed; the comparative design, in this second strategy, is based on the similarity of AR of the main wings; the designed configuration is named BW_2 . The results are reported in Table 3, and the sketch of the lifting system planform is depicted in Fig. 9-right. It directly emerges that, to fulfil the same TLARs, the BW_2 exhibits a reference surface significantly larger than that of the TW benchmark (+98%). Consequently, the wing loading of the individual lifting surfaces of the box wing is considerably lower than that of the TW main wing. The first causes an increase in wetted surface and hence in friction drag, whereas the second undermines the potential of the ‘best wing system’ to reduce the induced drag. Both these effects, hence, introduce significant penalisation of the aerodynamic performance of the BW_2 . Furthermore, the unnecessarily oversized lifting system causes

Table 3 Main data of the compared configurations. Double data refer to front/rear wings

	TW	BW_1	% Δ	BW_2	% Δ
S_w [m ²]	130/23	88/73	-32/-44*	131/126	1/-3*
AR_w	9.9	14.7/17.8	48/79*	9.9/10.2	=/3*
MTOW [kg]	77,170	82,760	7.2	86,850	12.5
W_{eo} [kg]	42,250	47,150	11.6	50,090	18.5
W_{wings} [kg]	6760	11,130	64.6	13,125	94.1
L/S [kg/m ²]	556	532/344	-4/-38*	344/198	-38/-64*
$L/D@cruise$	18.12	21.67	+16.6	16.89	-6.8

*Considering the TW main wing

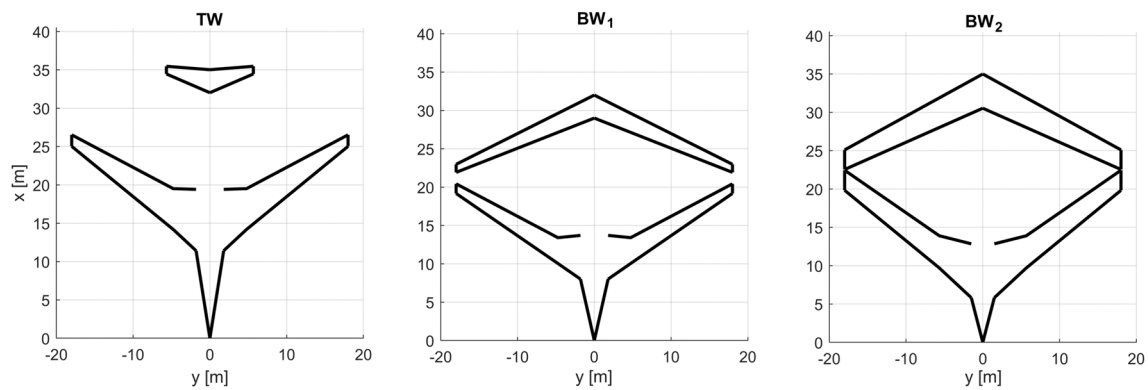


Fig. 9 Sketch of the lifting system planforms of the compared configurations

also a significant increase in wing structural weight (+94%), and hence MTOW (+12.5%); see Table 3. Also in this case, hence, the decision-making statement could easily be ‘no’ without any further investigations for this configuration.

Both the strategies highlight the potential contradictions behind the like-for-like strategy of BW development and the related comparative analysis between two architecturally and functionally different configurations. From one side, non-credible solutions are likely to be discarded in the initial conceptual design, to avoid the risk of unfeasibility in the more advanced design stages; on the other side, only very poor solutions in terms of expected performance could be designed. The two examples show that sticking to a like-for-like constrained design process when dealing with the initial development of a disruptive technology or concept can be ambiguous, leading to results that may be considerably worse than expected.

5.1.2 TLARs update

Even if the discussion is based on simplified models and related qualitative assessments, it emerges without ambiguity that keeping the same design requirements as a conventional aircraft proves to be thoroughly ineffective for the development of non-conventional box-wing aircraft. The need to maintain a direct like-for-like comparison strategy could therefore hide bias and introduce errors in the design development. In this regard, then, a second step of conceptual comparison is carried out, in which the set of TLARs is not kept as the same as the conventional benchmark, but is adapted to the functional-technical potential of the specific non-conventional architecture, i.e. the box-wing. Theoretically, some of the main potential benefits of a box-wing lifting system are: (i) the reduction of the induced drag, with a possible benefit in terms of lift-to-drag ratio; (ii) longitudinal stability and trim functions are inherently fulfilled by the lifting system, without the need to introduce additional non-lifting components, i.e. horizontal stabilizer; (iii) the increase

of the aircraft lifting capability with respect to a TW having with the same wingspan; this is achievable as the BW has two distinct lifting wings. Accordingly, a possible way to exploit the potential of the BW is to steer its design towards maximum fuel efficiency, while efficiently increasing the aircraft weight, i.e. increasing the payload, and at the same time maintaining the wingspan constrained at 36 m to be still compliant with the ICAO ‘C’ standard. The short-medium range aircraft sector is expected to significantly grow in the next years; hence, a next-generation aircraft design must prioritize high capacity and efficiency to meet the forecasted increase in air traffic demand [111], while prioritizing environmental sustainability [112, 113] and addressing the bottleneck of airport slots saturation [114]. Definitely, a basic requirement for the initialization of a novel aircraft design process may be: “the aircraft design must simultaneously address three key tasks: meeting the large expected increase in air traffic demand for short-medium routes, mitigating airport saturation issues, and reducing environmental and climate impact.” The functional features that this novel aircraft should have to accomplish these tasks could be: (i) increased passengers cabin capacity compared to the current aircraft operating in this market sector; (ii) limiting the overall size of the aircraft, especially the wingspan, to operate from the same aprons of the competitors (ICAO ‘C’); (iii) introduce technological solutions aimed to improve overall fuel efficiency. The box-wing features theoretically can match these tasks, hence justifying a related feasibility study. Thus, the TLARs reported in Table 2 are modified to redesign the BW by increasing the number of passengers from 186 to 310. This modification in the design requirements introduces the first major change in the development of the BW configuration with respect to the TW competitor; to allow the aircraft to accommodate the target number of passengers, it is necessary to reshape the fuselage, introducing a double-aisle cabin section, and hence an enlarged cross section; Fig. 10 reports the sketch of the two different cabin sections for the TW and the BW configurations. The BW fuselage section has width

equal to 5.39 m and height equal to 4.16 m and an overall length equal to 44.2 m, whereas TW fuselage section has a cross section diameter (d_{fus}) equal to 3.95 m, and an overall length (L_{fus}) equal to 37.6 m.

This box-wing configuration, named BW_3 , is designed to have main wing loading comparable to that of the benchmark 186-passenger TW aircraft. The results related to the two configurations are reported in Table 4, whereas the planforms are depicted in Fig. 11. The data reported in Table 4 suggest that the design of the BW_3 lifting system could have removed the critical issue of possible unfeasibility or on overall performance that have been highlighted in the examples of Sect. 5.1.1. The two horizontal lifting surfaces of the box wing, if considered individually, have similar geometric characteristics compared to the main wing of the TW; overall, the two configurations have comparable wing loading and aspect ratio of the main wing, as well as the same wingspan. Considering the design point lift-to-drag ratio, the BW provides a performance improvement; furthermore, the configuration can transport 66% of passengers more than the conventional benchmark, still operating from the same airport aprons.

Another approach that can be considered in terms of TLARs variation consists of maintaining the same number of passengers, equal to 186, but reducing the maximum wingspan b for the BW; this is another strategy to design the two lifting surfaces of the box-wing with features that are similar to that of the state of the art wings, hence possibly being far from the issues discussed in Sect. 5.1.1; the fuselage of the 186-passengers sized aircraft are the same. A similar approach has been also adopted for the box-wing aircraft studied in [115], for which also the boundary layer ingestion aft-mounted engines technology has been integrated.

The basic requirement steering the development of this aircraft, named BW_4 , nevertheless, is quite weaker that stated for the BW_3 , as only limited apron space gains are to be obtained. The sizing procedure in Sect. 4.1 was then used to design a box-wing with the TLARs of Table 1 and

Table 4 Main data of the compared configurations. Double data refer to front/rear wings

	TW	BW_3	% Δ	BW_4	% Δ
N° pax	186	310	66	186	=
S_w [m ²]	130/23	122/115	-6/-11*	73/69	-44/-47*
b [m]	36	36	=	28.8	-20
AR_w	9.9	10.5/11.3	6/14*	11.3/11.9	14/20*
MTOW [kg]	77,170	125,750	63	79,257	2.7
W_{eo} [kg]	42,250	68,590	62	43,877	3.8
W_{wings} [kg]	6760	14,567	115	8144	20.4
L/S [kg/m ²]	556	605/394	9/-29*	596/396	7/-29*
$L/D_{@cruise}$	18.12	20.28	11.9	19.5	7.6

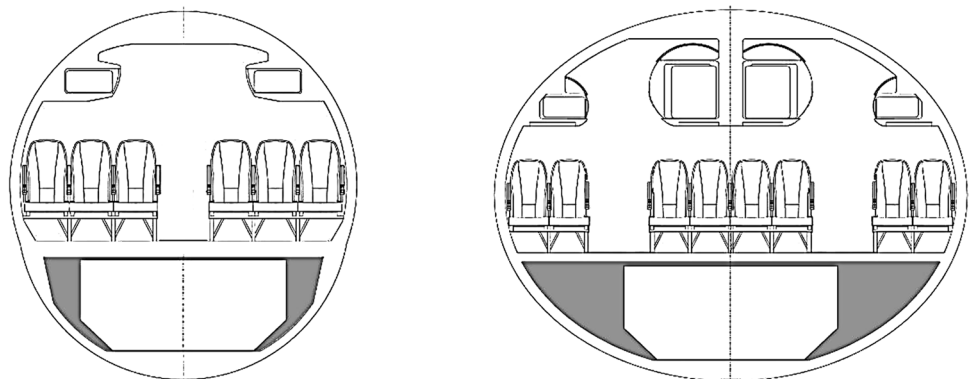
*Considering the TW main wing

changing only the maximum wingspan, limited to 28.8 m as that of the Embraer E190; the resulting aircraft's main features are shown in Table 4, and the planform is in Fig. 11. The BW_4 configuration therefore exhibits non-critical geometric and weight characteristics, and potentially a better aerodynamic performance at the design point measured in a 7.6% increase in lift-to-drag ratio.

Therefore, in the decision-making phase following the feasibility assessment, both the BW_3 and BW_4 configuration seem worth being approved for further investigations.

To initialise the comparative performance assessment, the lift-to-drag ratio curves for the design condition of $M=0.79$ and $h=11,000$ m (transonic) are discussed; lift and drag coefficients are computed according to the aerodynamic models implemented in the AEROSTATE code, see Sect. 4.1. The lift-to-drag ratio trends with respect to the lift coefficient (left) and generated lift (right) for the three configurations are reported in Fig. 12; given the simplified models used in this context of early sizing analysis, it may be speculative to make quantitative comparisons, but a few macroscopic considerations can be made. First, it emerges that BW configurations have better aerodynamic performance; it should be also noted that the BW_3 configuration

Fig. 10 Comparison of fuselage cross sections and cabin layout for 186- (left) and 310- (right) passengers arrangement



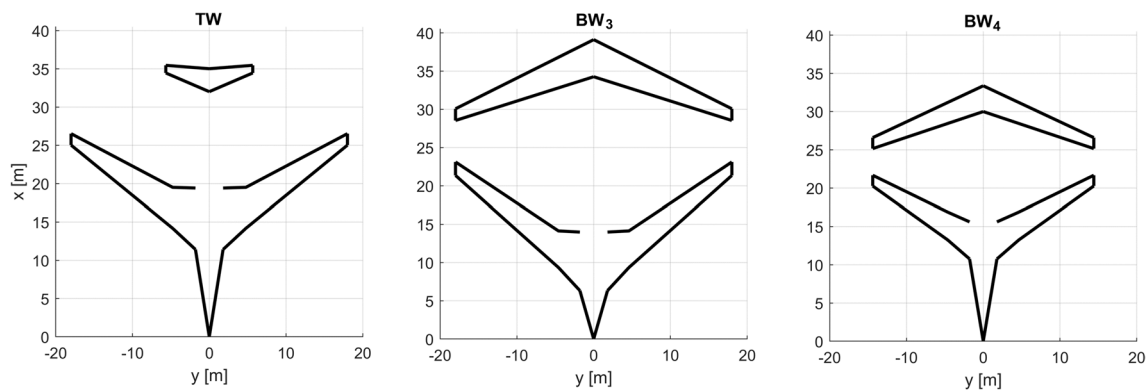


Fig. 11 Sketch of the lifting system planforms of the compared configurations

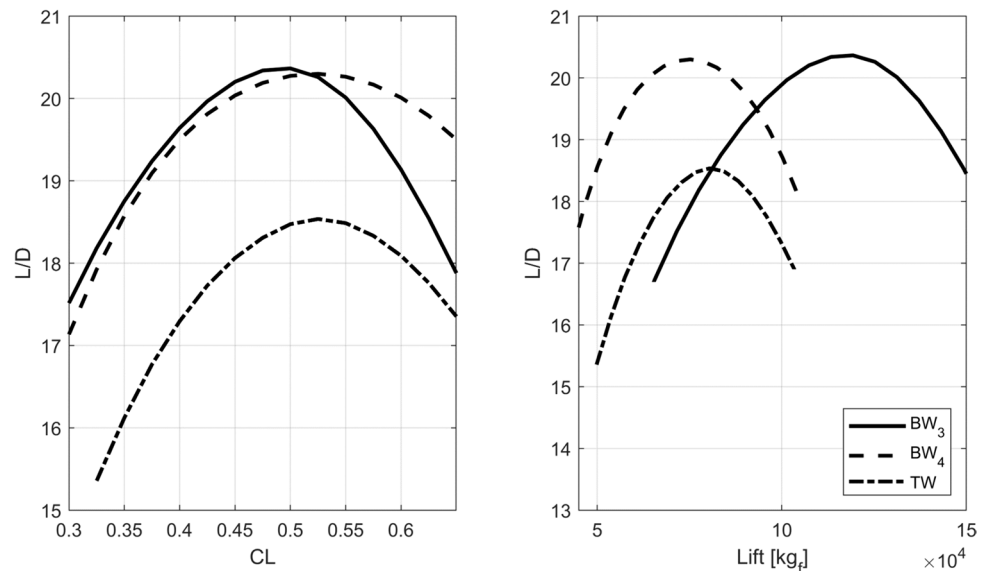
introduces penalising effects in terms of drag resulting from an enlarged and longer fuselage. In general, the most noticeable feature that emerges from these data is that the BW_3 configuration, while having competitive aerodynamic performance compared to configurations having a single aisle fuselage, is capable of generating much greater lift, and thus effectively equilibrating a larger weight. This is a key functional feature of the box-wing lifting configuration.

5.2 Preliminary performance comparison

The general and qualitative considerations outlined in Sect. 5.1 have highlighted the need to tackle the design of the box-wing configuration according to a different guideline, starting from the proper selection of TLARs. These, in fact, must be specifically tailored to boost the performance, functional, and operating potential of a complex product such as a transport aircraft. In the case of disruptive concepts, selecting design requirements only on the premise of the

need to directly compare the incremental contribution that can be provided to the state of the art could therefore lead to ambiguous, or even outright erroneous, design choices. In this section, it is therefore intended to briefly provide the comparative performance assessment derived from higher fidelity models than those used for the qualitative comparative characterisation proposed in Sect. 5.1, to provide a validation of the goodness of the suggested design choices. In this case, the aerodynamic and weight information (concerning the primary structural weight), provided as input to the mission simulator, are evaluated by means of CFD and FEM simulations, respectively; in this respect, reference is made to Sect. 4.2. The configurations selected for the refined performance comparative study are the benchmark TW (see TLARs of Table 1); a BW configuration (named BW_{308}) designed to transport 308 passengers and the other TLARs as the TW; a BW designed to transport 186 passengers (named BW_{186}), the wingspan equal to 28.8 m, and the other TLARs equal to the TW. The 3D representations

Fig. 12 Lift-to-drag ratio curves vs lift coefficient (left) and generated lift (right)



of the three configurations analysed are reported in Fig. 13. The fuselages of the 186-passenger aircraft are the same, while the BW-308 configuration has an enlarged fuselage section, as described in Sect. 5.1.2 and sketched in Fig. 10.

As far as the discussion of the present paper is not focused on the aircraft design activities, but on the comparative assessment of the two different architectures, the details on the development of the BW concepts are omitted, and an interested reader can refer to [116]. The geometry of the selected TW benchmark is the CeRAS CSR-01 aircraft [117], an open data platform specifically developed to be a reference for comparative studies. It is worth to underline that no design modifications or optimizations have been done for this reference aircraft; nevertheless, the performance assessments models used are the same for every configuration, specifically: *i*) to compute aerodynamic polar curves in different operating conditions the CFD model and RANS solver is set the same for TW and BW; *ii*) the FEM-based structural sizing to assess the primary structure weight, for both fuselage and lifting surfaces, feature the same modelling and loading conditions; *iii*) weight prediction models regarding common components (i.e. non-related to aircraft architecture), as systems, secondary structures, furnishing, and other operating items, are computed by means of the formulae reported in Ref. [102]. Table 5 summarizes the main features of the three aircraft; note that the harmonic range is not an input but it is computed by introducing the updated mass and aerodynamic performance data into the mission simulator; a convergence on the fuel consumption, considering the reserves and the diversion, is set, and the maximum range achievable with the reference fuel quantity is calculated (cf. Section 4.2).

The comparison of the lift-to-drag ratio can provide a general picture of the aerodynamic performance of the three configurations. Figure 14 shows the L/D curves as a function of the generated lift at the design point, i.e. $M=0.79$ and $h=11,000$ m, calculated using compressible steady RANS simulations; to reduce computational time/cost, only the fuselage and the lifting systems (i.e. aircraft wing-body) have been modelled, whereas the drag contribution of nacelles and the vertical tail has been calculated by means of simplified equations [101]. Three interesting observations can be made: (i) the BW-308 configuration has the best aerodynamic performance; (ii) also the BW-186 outperforms the aerodynamic performance of the reference TW, but by

a lower margin; (iii) the BW-308 configuration, with the same wingspan as the TW benchmark, is able to generate a significantly larger lift, and therefore can equilibrate a much larger weight in flight, and with higher lift-to-drag ratio.

Using the mission simulation tool introduced in Sect. 4.2, the mission performance of the three aircraft can then be compared; to discuss this comparison, the range of the harmonic mission of the TW benchmark is taken as a reference for the three aircraft, cruise Mach and altitude are the same, 0.79 and 11,000 m, respectively; the comparison is assessed in terms of block fuel consumption. The propulsive performance, i.e. the thrust-specific fuel consumption, is kept the same for all the configurations, to avoid introducing bias deriving from propulsive technology. Nevertheless, an aeropropulsive difference could have an impact on aerodynamic performance: the BW has an aft-fuselage engine installation, and some detrimental interference effects [118] could be removed with respect to a traditional under-wing installation. However, due to the general level of the comparative discussion, these aspects can be reasonably neglected. Figure 15 shows the trajectories of the three aircraft (top), the time evolution of the lift-to-drag ratio (centre) and of the fuel flow (bottom).

Table 6 shows the general mission performance results in this reference case, in terms of block fuel mass (m_{bf}) and block fuel per passenger-kilometre; it can be seen that the BW-186 could introduce a fuel saving per passenger-kilometre of 8%, while the BW-308 configuration, carrying 66% more passengers, consumes 32% more fuel, but with

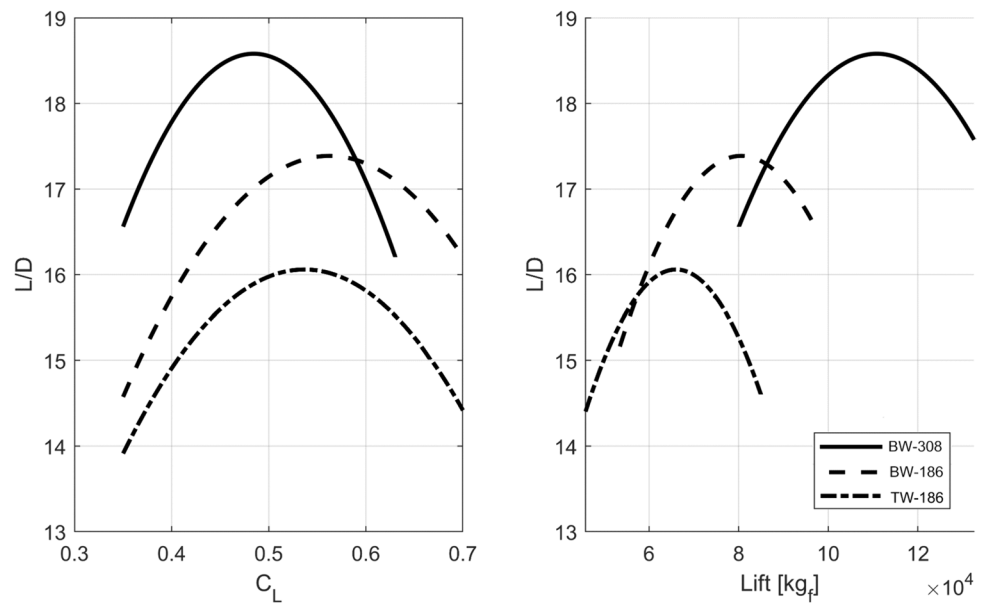
Table 5 Main data of the compared configurations

Key Features	TW	BW-186	BW-308
Passengers number	186	186	308
Harmonic range [km]	4791	5180	5722
MTOW [kg _f]	76,824	78,130	125,126
W_{oe} [kg _f]	42,054	43,360	68,866
$W_{oe}/MTOW$	0.547	0.554	0.550
L_{fus} [m]	37.5	37.5	44.2
d_{fus} [m]	3.95	3.95	5.39
h_{fus} [m]	3.95	3.95	4.16
b [m]	34.1	28.8	36
S_w [m ²]	122/32	73/69	118/109
AR_w	9.5	10.9/11.8	11.3/11.9

Fig. 13 Artistic 3D views of the compared configurations



Fig. 14 Lift-to-drag ratio curves vs lift coefficient (left) and generated lift (right)



a reduction in fuel consumption per passenger-kilometre of 20%. In this latter case, however, given the functional and operating differences between the two aircraft, using only this metric as an all-inclusive performance comparison may hide ambiguities or neglect other comparative considerations.

Indeed, let us consider the entire operating envelope of the three compared aircraft, which can be graphically effectively represented by means of the payload-range diagram, see Fig. 16. From this graph it clearly emerges that:

- (i) the BW-186 could introduce some fuel consumption reductions (albeit not overly significant), but it does not introduce tangible operating advantages in the overall scenario: the question therefore is whether the industry would be justified in taking the risk correlated to the development of a totally disruptive concept, to obtain limited performance advantages, or to continue more reliably in the path of evolutionary incremental improvement;
- (ii) in the case of BW-308, in addition to an advantage in fuel consumption per passenger-kilometre of around 20%, a completely different operating scenario is observed compared to that of the conventional TW; the payload-range envelope is significantly larger, with an increase in the maximum number of passengers of 66%, and an increase in the maximum range for the same TW number of passengers of 95% (mainly due to a larger available volume for wing tanks); this performance is achieved with the same wingspan of the conventional TW, thus without implying any penalty in terms of required apron

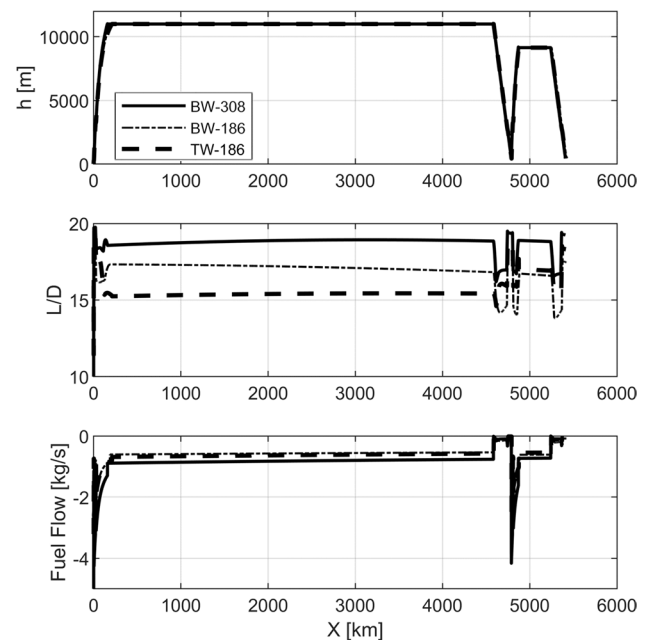


Fig. 15 Evolution of mission simulation main outcomes for the compared configurations: trajectory (top), lift-to-drag ratio (middle), fuel flow (bottom)

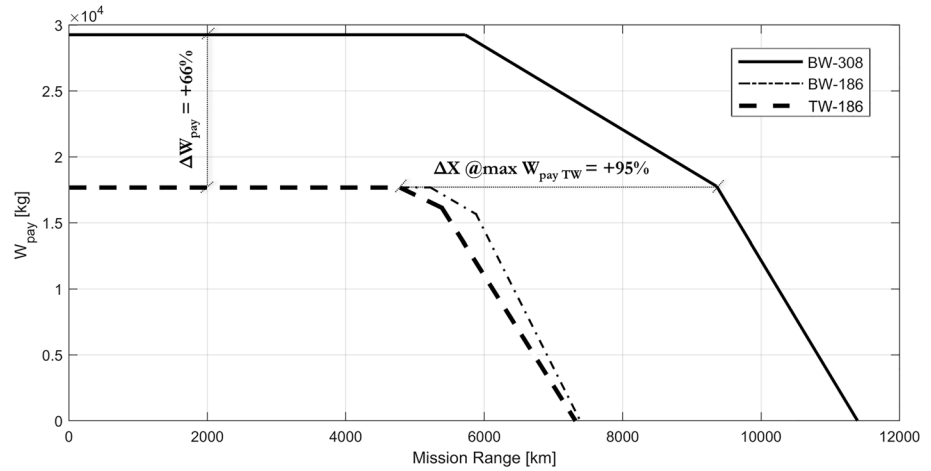
space and therefore providing a possible relief of airport saturation issues.

From this comparison it can be commented on what was anticipated in a more general perspective in Sect. 2.4: using disruptive innovations to only introduce incremental gains to the state of the art may be limiting, while exploiting such innovations to meet operating, functional, or performance

Table 6 General mission performance comparison

Conf	X [km]	Pax	$\Delta\%$ pax	m_{bf} [kg]	$\Delta\%$ m_{bf}	$m_{bf}/(\text{pax-range})$ [kg/pax-km]	$\Delta\%$ $m_{bf}/(\text{pax-range})$
TW-186	4791	186	Ref	13,670	Ref	0.01534	Ref
BW-186	4791	186	=	12,587	-8%	0.01412	-8%
BW-308	4791	308	+66%	18,108	+32%	0.01227	-20%

Fig. 16 Payload-range diagram comparison



goals that cannot reasonably be achieved by the evolutionary development of traditional technologies may open up new scenarios; from these, it is possible to increase the detail of investigation of the innovative concept, and foster its subsequent detailed development and possibly its actual implementation.

6 Discussion

The development of disruptive technologies, as its name suggests, involves the need to disrupt established concepts and go beyond the typical procedures, methodologies and technological evolutionary processes. Through the box-wing case study, it was intended to highlight how for the development of unconventional aviation technologies it might be appropriate to leave behind direct, incremental comparisons with the state of the art. While this latter approach is consistently effective, especially when considering canonical requirements and metrics, it could in some cases lead to the omission of functional or performance benefits not contemplated for the traditional technologies. The discussion that is intended to be offered here, therefore, is not aimed at stating which architecture or configuration is better than the others, but it would like instead to provide a different perspective on the design paradigms of novel transport aircraft, especially in an era where major technological transitions are expected. In particular, through the example of the box-wing

configuration, it was intended to show how advanced challenges, such as the need to simultaneously meet the significantly increased demand from market expansions, the reduction of pollutant and climate-changing emissions, and the increasing problems of airport saturation, can lead to deviation from an evolutionary development of the ‘system’ aircraft; when an innovation is introduced to try to meet the new basic requirement(s), the like-for-like benchmarking approach should also be relaxed. Compare canonical performance for configurations having different functions could still lead to biasing of comparisons and impair the concept of fairness. This rationale could be extended to different breakthrough innovations currently under investigation for the next-generation aircraft. For example, it is possible to refer to the basic requirement of ‘carbon neutral aviation’ that is being set as a guideline by different policymakers [119, 120]; in this case, the evolutionary approach is inherently reasonably unavailable to achieve this goal, and the embedded characteristics of disruptive technologies may introduce new paradigms of aircraft design conception. In this context, for example, if electric or hybrid-electric propulsion solutions are being considered to drastically reduce greenhouse emissions, the technological limitations of batteries, which even under future predictions result in very significant weight additions [121, 122], must be taken into account. Steering the design of the hybrid-electric aircraft aiming at minimizing MTOW or direct operating costs, as is usual for traditional aircraft, could result in design choices

that push technological innovation away from achieving the basic requirement, i.e. fuel consumption and emission reductions. Different design paradigms must be introduced, capable to exploit the maximum functional or performance potential of the considered technology bricks, also accepting penalizations in canonical figures of merit.

Here what emerges is that, when technologies and architectures deviating from the state of the art are to be evaluated and developed, before proceeding simply with an incremental approach, it might be more effective to:

- (i) evaluate the specific functional features of the investigated technology and the related performance potential;
- (ii) assess the existence of basic requirement(s) that can be met in a specific and peculiar way by these features;
- (iii) clarify whether or not the evolutionary development of established traditional technologies can meet this basic requirement(s);
- (iv) in case this is reasonably not possible, identify new paradigms for disruptive technology development with the purpose of meeting the basic requirement.

The definition of the detailed specification, and of the actual start of the design process through the different design, refinement and optimization steps, follow these points; in a like-for-like approach, on the other hand, the previous *i-iv* points are typically neglected.

7 Conclusions

This paper aims to present a general discussion on the problem of the conceptual development of disruptive aeronautical innovations and the related most viable ways of benchmarking them with the state of the art. This discussion derives from the need to identify reliable paths for the development and benchmarking of breakthrough innovations (such as non-conventional lifting configurations), that could enable the performance and functional potential of such innovations to be fully revealed and exploited. Indeed, when a concept differs significantly in design and functions from state-of-the-art technologies, it may be necessary to deviate from the latter and identify different requirements and figures of merit specifically tailored to the new concept to be introduced. In this work, it has been qualitatively shown that maintaining a ‘like-for-like’ approach with the state of the art, i.e. strictly maintaining the same requirements, figures of merit, or constraints between traditional and non-conventional configurations, in some cases may be misleading and cause flawed design development of the innovative concepts. In fact, the ‘like-for-like’ approach is

frequently considered the only one capable of offering fair design and performance comparative analyses between the different configurations analysed. In general, this is true when evaluating evolutionary technological innovations, i.e. those technological advancements that aim to introduce an incremental contribution to the state of the art. On the other hand, when analysing breakthrough innovations, which often have different functional characteristics compared to the established technological scenario, the ‘like-for-like’ approach may have the opposite effect, introducing bias and skew in the design development of the innovative concept. This aspect was discussed and commented on in the paper by means of the example of the box-wing lifting configuration. This architecture, indeed, introduces functional aspects that differ from the tube-and-wing configuration, which is largely the most established for commercial air transport. Introducing and optimising the box-wing configuration starting from the same requirements as the current benchmarks, with the only purpose of evaluating potential incremental benefits, is penalizing the development of such a concept. Instead, it is necessary to identify the most suitable set of top-level design requirements in order to exploit its peculiar characteristics, with the aim of enabling new operating or performance domains currently unlikely to be achieved through evolutionary technological development. Hence, the main outcome is the need to break away from the traditional comparative paradigms with conventional aircraft; an innovative and disruptive concept must be investigated to its full potential, also with the aim of identifying new modes and concepts of utilization. The conclusions proposed in this paper, however, are not only limited to the case of the box wing, which is just used as an example to support the discussion; indeed, these can be extended and adapted to many other breakthrough aeronautical technological innovations.

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Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interests The authors declare no competing interests.

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