Unconventional aircraft for civil aviation: A review of concepts and design methodologies★

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ARTICLE INFO

Keywords:
Unconventional aircraft
Sustainable aviation
Future aircraft
Aerodynamic shape optimization
Multidisciplinary design optimization
Fuel-burn

ABSTRACT

In recent decades, the environmental impacts of aviation have become a key challenge for the aeronautical community. Advanced and well-established technologies such as active flow control systems, wing-tip devices, high bypass ratio engines, composite materials, among others, have demonstrated fuel-burn benefits by reducing drag and/or weight. Nevertheless, aviation remains under intense pressure to become more sustainable. For this reason, there is a strong drive to explore unconventional aircraft with the aim of reducing both environmental emissions and Direct Operating Cost. This paper presents the current state-of-the-art in the development of future aircraft for civil aviation. The literature review is conducted through an appropriate search protocol to ensure the selection of the most relevant sources. After a brief historical background, progress in the design and development of several unconventional aircraft configurations is presented. Concepts such as Blended/Hybrid Wing Bodies, nonplanar wing designs, next-generation propulsion technologies that are tightly integrated with the airframe, among others, are reviewed. Special attention is given to design methodologies (level-of-fidelity), cruise altitude, aerodynamic performance, and fuel-burn benefits over conventional configurations. The primary contributions of this review are i) a detailed survey of the design characteristics of unconventional aircraft for non-specialists, and ii) a comprehensive review of the literature detailing past and current design trends of such configurations for specialists.

Contents

★This article is attributed to the research project entitled "Methodologies for designing, optimizing, and evaluating possible unconventional aircraft configurations for future civil aviation", which is funded by the National Council for Scientific and Technological Development - CNPq (grants 141950/2017-0 and 203402/2019-7). Although every effort has been made to ensure accuracy, the information contained in this publication is subject to the possible uncertainties of the described technologies. The authors recommend a constant review, bearing in mind the progress in aircraft design and computational aerodynamics, as well as the possible changes in government and environmental regulations. The authors disclaim liability for any loss, howsoever caused, arising directly or indirectly from reliance on the information in this article.

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Nomenclature

Abbreviations

ACARE	Advisory Council for Aeronautics Research in Europe
BLI	Boundary Layer Ingestion
BW	Box-Wing
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
CFD	Computational Fluid Dynamics
CTW	Conventional Tube-and-Wing
DLR	German Aerospace Centre
DOC	Direct Operating Cost
EIS	Entry into Service
ERA	Environmentally Responsible Aviation Project
FE	Finite Element
HLFC	Hybrid Laminar Flow Control
HWB	Hybrid Wing Body
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LFC	Lifting Fuselage Concept
MDO	Multidisciplinary Design Optimization
NACRE	New Aircraft Concepts Research
NASA	National Aeronautics and Space Administration
NLF	Natural Laminar Flow
NPV	Net Present Value, MUSD
RANS	Reynolds-Averaged Navier-Stokes
SBW	Strut-Braced Wing
SFC	Specific Fuel Consumption
SUGAR	Subsonic Ultra Green Aircraft Research
TBW	Truss-Braced Wing
TRL	Technology Readiness Level

Symbols

Æ	Aspect Ratio
C_{D0}	Zero-lift drag coefficient
e	Span efficiency factor
L/D	Lift-to-Drag ratio
ML/D	Aircraft Mach Lift-to-Drag ratio
q_∞	Dynamic pressure
U_∞	Freestream speed
W/S	Wing loading
ρ_∞	Fluid density

1. Introduction

According to the International Air Transport Association (IATA), air traffic tends to double every 15 years with an average growth of 4.4% per annum [1, 2]. Despite the current setback caused by the COVID-19 crisis, it is expected that air traffic will recover quickly and resume its normal growth rate [3]. In this context, the aeronautical sector faces a critical environmental challenge in terms of reducing the harmful effects of aircraft emissions on human health and climate change [4].

Many countries have recognized the need to address global climate change and have adopted a set of ambitious targets to reduce emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x) [5]. For instance, the Advisory Council for Aeronautics Research in Europe (ACARE) and the National Aeronautics and Space Administration (NASA) are already targeting these issues in short-term and long-term goals, which are periodically reviewed and updated by Committee on Aviation Environmental Protection (CAEP). For more details refer to the standards reported in [6]. Airframe and engine noise also raise similar concerns, and discussions about novel solutions to aeroacoustic problems can be found in [7, 8, 9]. Most of these targets require a substantial commitment to research and development of new technologies, i.e., potential future benefits can be achieved if we move away from traditional concepts and introduce new technologies in many fields such as aerodynamics, materials, structures, engines, and systems. No single technology provides the entire solution by itself, but many are complementary and can be combined [10]. This multidisciplinary approach has provided a framework for setting standards in the design of new aircraft configurations, while meeting tighter environmental constraints (emissions and noise) [11, 12, 13].

Based on this context, progress in unconventional configurations has focused on the reduction of noise and emissions, in particular CO_2 and NO_x, while at the same time reducing Direct Operating Cost (DOC), which includes all costs associated with operating and maintaining an aircraft over its entire life cycle [14, 15, 16, 17]. The addition of important environmental objectives has changed the way the aeronautical community foresees aircraft development in the future and has stimulated the development of numerous innovative technologies. Several literature reviews summing up challenges, opportunities, and benefits of such technologies have been already published. If readers are interested in any of these technologies, we recommend searching in the following sources: for drag reduction (including viscous drag, wave drag and induced drag) [18, 19, 20, 21, 22, 23, 24, 25]; for weight savings (including advanced composites and alloys) [26, 27, 28, 29, 30, 31, 32, 33]; for sustainable fuels (including biofuels and liquid-hydrogen) [34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]; for next-generation propulsion technologies such as open rotors [45, 46, 47, 48], distributed propulsion [49, 50, 51, 52, 53, 54], Boundary Layer Ingestion (BLI) [55, 56, 57, 58], and electric/hybrid/turboelectric aircraft [59, 60, 61, 62, 63, 64, 65, 66].

Although these technologies have the potential to increase the aircraft efficiency, the challenges of their implementation require extensive research and development efforts towards reducing aircraft emissions, as well as addressing trade-offs between different objectives. As a result, a great number of experiments and simulations are still being developed, in order to assess the overall benefits of various new technologies [67, 68]. Despite the efforts to date, there remains considerable uncertainty in terms of the potential fuel-burn, emissions, and noise reductions associated with the various proposed technologies.

Recognized aircraft design companies such as Airbus and Boeing, as well as research institutions and academia (NASA, DLR, ONERA, Bauhaus Luftfahrt, among others) are working on a variety of unconventional configurations. All these concepts aim to increase the ability to transport as much payload over the longest distance with the least amount of required energy or fuel as possible. Although these designs are only promising concepts, they offer a glimpse into the future [69]. These configurations provide benefits on two sides: by themselves due to better aerodynamics and/or lighter structures, and partly because they serve as platforms to assess the overall benefits of various new technologies, thus increasing the overall advantages.

This article aims to provide a survey of relevant research in next-generation aircraft that can replace current regional, single-aisle, and twin-aisle aircraft. The main objective is to provide a detailed overview of the estimated benefits of unconventional configurations over conventional aircraft. We also highlight the importance of the use of Multidisciplinary Design Optimization (MDO) methods to assess different technologies along with conflicting requirements. The reports discussed in this work were identified based on the following methodology. Reports describing performance comparisons (in terms of fuel-burn benefits) between unconventional configurations and conventional tube-and-wing (CTW) aircraft are included. Literature reviews of related topics are also included. Reports based on disciplines (i.e., without any reference to unconventional aircraft design) are excluded. Reports focused on the design of different aircraft categories such as military, general and urban aviation, supersonic transports, and Unmanned Aerial Vehicles, are also excluded. The synthesis of the review process is provided in Appendix A.

The rest of this paper is organised as follows: a historical background is provided in Section 2. A brief description of MDO frameworks that have been used to design unconventional configurations is provided in Section 3. Section 4 is devoted exclusively to the description and analysis of unconventional configurations, and provides some very rough ranges of estimates of the potential of each configuration. In Section 5, there is a discussion of cruise altitude in terms of the challenges it causes as well as its importance to climate change impact. Conclusions are given in Section 6.

2. Historical Background

The first flight of the Wright brothers in 1903 and the first flight of Santos-Dumont in 1906, were impressive proofs of concept but still far from suitable for practical use. Nevertheless, these heavier-than-air machines provided the foundation for the development of practical aerial navigation during the pre-war years. At the end of 1910, Glenn Curtis, whose biplane became the first to take-off from the deck of a ship, began to test planes as a platform for weapons. This last achievement marked a design trend for the next 35 years of aviation history, which was dominated by military applications [70]. Progress in aerodynamics between World Wars I and II centered on the introduction of thick airfoil sections, the development of better flight controls and effective high-lift devices [71]. These advances resulted from essential theories such as viscous flow and boundary layer theory by Prandtl, ideal fluid flow by von Karman, flight dynamics by Melvill Jones and compressible fluids by Taylor [72].

In 1935, Busemann [73] developed the wing sweep concept, which allowed aircraft to fly at higher speeds. The U.S engineers highly appreciated these benefits during World War II, incorporating this technology into new designs. The first two U.S. aircraft with 35° of sweep were both subsonic, the Boeing B-47 bomber and the F-86 Sabre [74]. At that time, R.T. Jones [75, 76] gained a critical understanding of the benefits of sweep and promoted its use for high-speed aircraft. Important contributions include swept-wing theory and the supersonic area rule. Based on these developments, large-scale strategic bombing campaigns were

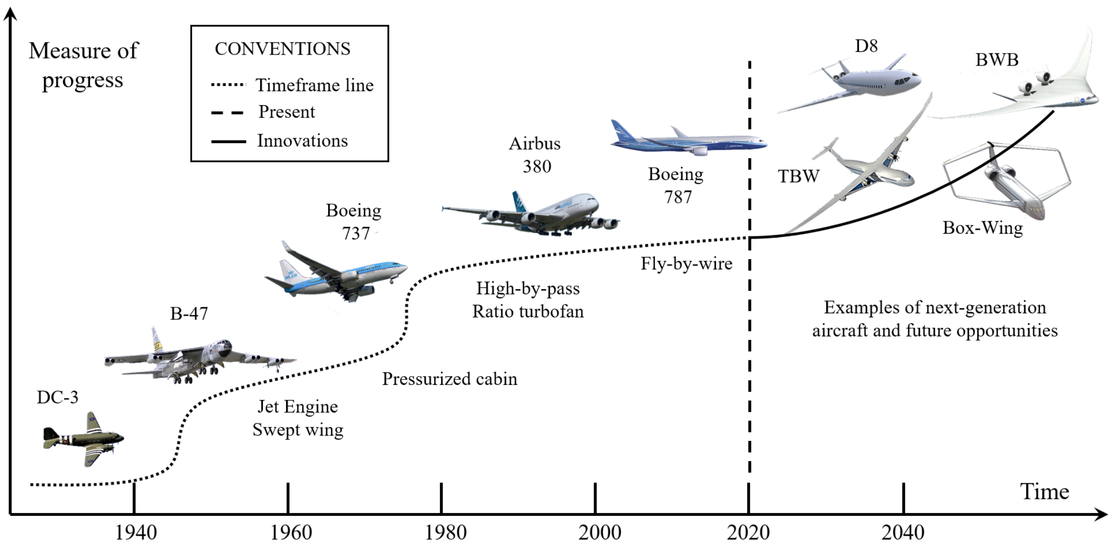


Figure 1: Progress in aircraft design of commercial airliners, from conventional designs to next-generation aircraft.

launched, fighter escorts introduced and the most versatile airplanes allowed precise attacks on small targets with dive bombers and fighter-bombers [77].

By the time World War II came to a close, commercial aviation expanded rapidly using mainly ex-military aircraft to transport people and cargo. Companies increased the production of such an aircraft and more than 10000 Douglas DC-3's were manufactured and converted for civilian missions [78]. From the introduction of the DC-3 in 1936 to that of the DC-7 in 1956, more than 16000 aircraft were manufactured using mainly a scaling factor of the engine power, wingspan, and fuselage length, resulting in increased speed and payload capacity [79]. For this reason, the DC-3 is one of the most successful aircraft in history. Even today, there are small operators with updated DC-3's in revenue service and as cargo aircraft across the world [80]. As the Boeing company had developed innovative and important bombers, revolutionary concepts such as the Boeing 707 and Boeing 727 enabled progress in jet engines and structural design. During the 60s, Boeing produced a number of short-haul jet-aircraft designs, and created a new aircraft to replace the 727 on short routes. Thus, the Boeing 737 made its first flight in 1968, and its design features have effectively become a blueprint for most jet airliners that have been manufactured since then [81, 82]. This achievement was boosted by extensive experimental and theoretical work on supercritical wings during the late 70s, such as the ones reported by Whitcomb et al. [83, 84]. The success of the Boeing 737 allowed it to stay in service for over half a century with several modifications applied to the fuselage, wings, empennage, and propulsion system (Boeing 737 family) [85, 86, 87]. Subsequently, other companies such as Airbus, Embraer, Bombardier, etc. have adopted this conventional configuration to design and manufacture their own aircraft [88].

To illustrate this point, Fig. 1 shows the design evolution of commercial aircraft measured in terms of their overall progress in terms of capabilities, initially defined in terms of range and fuel efficiency, now increasingly defined by noise and emissions, with fuel efficiency remaining critical. Three main lines define the conventions on this figure. The first line (dotted line) represents the progress up to 2020, which is a kind of stair-step progress focused on significant technological breakthroughs that occurred until the launch of the Boeing 787. These breakthroughs include fly-by-wire systems, the use of composite materials, laminar flow control technologies, high bypass ratio turbofans, among others, which in turn offer improved fuel efficiency, reducing operating costs and emissions. It is observed that the general layout of the CTW aircraft has remained predominantly the same, as this configuration represents a very efficient compromise between aerodynamics and weight, without compromising the safety and comfort of the passengers at high altitudes, i.e., the CTW aircraft is very well understood thanks to years of design, manufacturing and operating experience. That is the reason why the entire fleet of Concorde aircraft was retired on October 2003, i.e., the Concorde deviated from the evolutionary path traced by successful airplanes that preceded it [82]. Although the Concorde was a great technical achievement, it was a commercial failure. Only 20 aircraft were manufactured, and fuel cost and ticket prices were always high [74]. Currently, there is a renewed interest in developing civil supersonic transports and supersonic business jets. Some literature reviews described the progress of these concepts, indicating that mitigation of sonic boom intensity is relevant if the vehicles intend to operate over land. There are also important design challenges such as airframe weight and propulsion-airframe integration, which need to be addressed to made these concepts more fuel-efficient and cost-effective [89, 90, 91, 92]. Such developments are not considered further in this review.

Figure 2: Unconventional aircraft configurations that could be critical for achieving improved fuel efficiency and reduced emissions. A conventional aircraft (centre) is surrounded by concepts for more efficient designs - clockwise from top left: box-wing configuration, strut-braced-wing configuration, lifting-fuselage configuration, and hybrid-wing-body configuration. Credits: Thomas Reist and David Zingg - University of Toronto Institute for Aerospace Studies.

The second line (dash line) represents a point today, which is the culmination of progress made over the course of approximately 50 years of industrial, governmental, and academic efforts in the commercial age. After half a century manufacturing the current CTW configuration, concerns about the impact of aviation on climate change require major technologies and investment to satisfy the needs of the vision for sustainable aviation [6]. These challenges have a direct impact on the efficiency of air transportation, mainly on aerodynamic, structural and propulsion technologies. In this context, the aeronautical community is aware that current CTW aircraft may be unable to meet these challenges or may not be the optimal solution. Therefore, major innovations are urgently required (black-solid line), such as unconventional configurations, since they have the potential to provide step improvements in the medium term [93, 94], which justify the cost and risk associated with their development. There are many unconventional configurations that offer step-change benefits, some relying on key emerging technologies and integration concepts, and some with key challenges to overcome. The state of research and development varies for each concept; however, several green aerospace projects (NACRE [95], ERA [96], SUGAR [97, 98, 99, 100, 101], Clean Sky [102, 103], NASA N+3, N+4 programs [104, 105], SE^2A [106], among others) have identified the technological feasibility of the Blended Wing Body (BWB), Hybrid Wing-Body (HWB), hybrid-electric configurations, the Box-Wing (BW), the Strut-Braced Wing (SBW), the Truss-Braced Wing (TBW), and the Double-Bubble with aft-integrated BLI propulsion. These concepts, which are expected to play a major role in reducing global aviation carbon emissions for the longer-term future (2035 onwards), are further discussed in section 4. Figure 2 shows a rendering of some unconventional concepts that have been studied by the aeronautical community.

3. Brief Review of MDO Frameworks

The evaluation of unconventional aircraft and novel technologies is often done for a specific set of requirements, usually due to limitations in terms of experience and methods that would be needed for an extensive assessment. Therefore, MDO has emerged as a methodology to address the complex design trade-offs in next-generation aircraft. Several MDO frameworks with different levels of complexity and fidelity have been employed in the design synthesis of unconventional configurations, from theoretical/semi-empirical methods to more complex high-fidelity aerostructural design optimization tools. Some authors such as Sobieszczanski-Sobieski and Haftka [107], Vos et al. [108], Martínez-Val and Pérez [109], La Rocca [110], Martins et al. [111, 112], Papageorgiou et al. [113], Kenway et al. [114] and Mcdonald et al. [115] have presented complete reviews of old and recent advancements in MDO for aeronautic applications.

Based on the above literature reviews, a summary of the level of fidelity, disciplines, computational cost, and accuracy is given in Fig. 3. The following observations can be made:

- The oldest MDO tools, which have the lowest computational cost, are based on semi-empirical and linear methods, which continue to be used due to their ability to generate quick aerodynamic and mass estimations. However, mission output calculations must be re-evaluated at the later stages of the design process, especially for the transonic conditions. Since most low-fidelity methods use discrete variables such as the number of engines, wing position, tail location, etc., gradient-free optimizers are best suited to explore wide design spaces. Particle Swarm Optimization and Genetic Algorithms are the most well-known methods that are widely used since they are potentially capable of finding the global optimum for complex functions. Some examples of MDO frameworks like these are: Initiator [116], a preliminary sizing tool for conventional and unconventional aircraft configurations developed by Delft University of technology; PyInit [117], a physics-based design tool developed by Technische Universitat Braunschweig; AEROSTATE tool [118], a conceptual design tool based on a constrained aerodynamic optimization procedure developed at University of Pisa; JPAD code [119], a conceptual design framework for advanced turboprop aircraft developed by University of Naples Federico II; The tool FRIDA (FRamework for Innovative Design in Aeronautics) [120], a multidisciplinary conceptual robust design optimization framework developed by Roma Tre University; and RDS aircraft design software [121] developed by Conceptual Research Corporation.

- Medium-fidelity methods are more complex than low-fidelity tools. The main difference is the use of non-linear potential or Euler solvers which allow the solution of rotational, non-isentropic flows. Thus, they are fairly reliable for predicting wave drag due to their ability to capture the correct position of shock waves. Furthermore, mass estimation methods include elementary physics-based analysis for primary structures, and semi-empirical and statistical methods for secondary structures, thus providing better accuracy when aerodynamic loads and structural analyzes come up with a coupled design. Some solvers also include 1D approaches for characterizing the propulsion system. In short, these methods provide consistent results to full working precision at very reasonable computational cost. Some examples of MDO and multi-fidelity modeling tools like these are: PrADO [122], a preliminary aircraft design tool for unconventional aircraft configurations developed by Technische Universitat Braunschweig; SUAVE [123, 124], an open-source environment for future aircraft design developed by Stanford University; TASOPT [125], a computational tool developed by Massachusetts Institute of Technology which involves noise and emissions constraints into its main MDO environment; EDS [126], a physics-based software developed by Georgia Tech capable to estimate fuel-burn, source noise, exhaust emissions, performance, and economic parameters for potential future aircraft designs; FLOPS code [127] developed by NASA to design new aircraft configurations and evaluate the impacts of advanced technologies; GENUS framework [128], a modern computer-based design method which uses a multivariate design optimization environment developed by Cranfield University; and Faber [129], a low-to-medium fidelity tool developed at the University of Toronto.
- Due to advances in high-performance computing, Reynolds-Averaged Navier–Stokes (RANS) simulations and Finite Element (FE) analysis have been successfully applied in aircraft conceptual design studies, particularly in aerodynamic shape optimization and aerostructural design optimization problems [130]. These high-fidelity frameworks are able to evaluate large numbers of design variables, design points, and constraints, enabling improvement of current designs and reducing the risk associated with the development of unconventional configurations. The choice of the optimization algorithm plays a key role when solving this kind of problems, and gradient-based algorithms combined with the adjoint method have demonstrated rapid convergence when controlling a wide range of design variables. The main disadvantage of gradient-based algorithms is that they find a local rather than a global optimum. However, this problem can be mitigated through the use of a gradient-based multi-start algorithm [131, 132]. Some examples of high-fidelity tools that have been used to design unconventional aircraft are: Jetstream [133, 134, 135], a multi-fidelity MDO framework with high-fidelity aerodynamic shape optimization developed at the University of Toronto; SU2 [136], an open-source tool written by Stanford University in cooperation with the Boeing company to solve multiphysics and optimization problems on the basis of unstructured meshes; OpenMDAO [137], an open code written by NASA in cooperation with University of Michigan to facilitate gradient-based optimization and computation of derivatives. The University of Michigan has also developed MACH-Aero, an open-source high-fidelity framework which uses pyOpt [138] to handle large-scale optimization problems, and DAFoam [139] and ADflow [140] for flow simulation and adjoint computation. Further examples include the ONERA elsA CFD software [141], a multi-purpose tool for applied CFD and multi-physics; KADMOS [142], an MDO framework developed by Delft University and supported by the AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) innovation project [143, 144]; ADEMAO [145], a multi-fidelity design, analysis, and optimization environment for future transport aircraft developed by Technische Universitat Braunschweig; and various software tools developed by NASA and Boeing [146]. Specific details of each software are beyond the scope of this review.

It is worth emphasizing that the estimates of the benefits of new configurations can vary quite a bit depending on the assumptions made and tools used. For example, the SBW concept proposed by Chau and Zingg [129] assumes current technology levels other than the configuration, involving conceptual-level MDO and high-fidelity aerodynamic shape optimization to study shock formation and boundary-layer separation within the wing-strut junction; while others, such as the Double-Bubble D8 by Drela [147], involves various future technologies such BLI, natural laminar flow and a lifting fuselage, although the conceptual design is based on low-to-medium fidelity approaches. In the former case, the benefit of the configuration is calculated in comparison to a CTW using current technology. In the latter case, the benefits come from future technologies, relative to today's aircraft. Furthermore, there is a clear trade-off between the efficiency of the design and the certainty that all requirements will be met when the design is subjected to better analysis methods, i.e., the benefits of the configurations from early conceptual studies to more recent high-fidelity studies have become clearer as the level of fidelity has increased.

4. Unconventional Configurations

This section looks at important unconventional aircraft design research that has been done by industry, government entities, and academia. In industry, new aircraft and engines are designed to generate income for the manufacturer, which means they have to

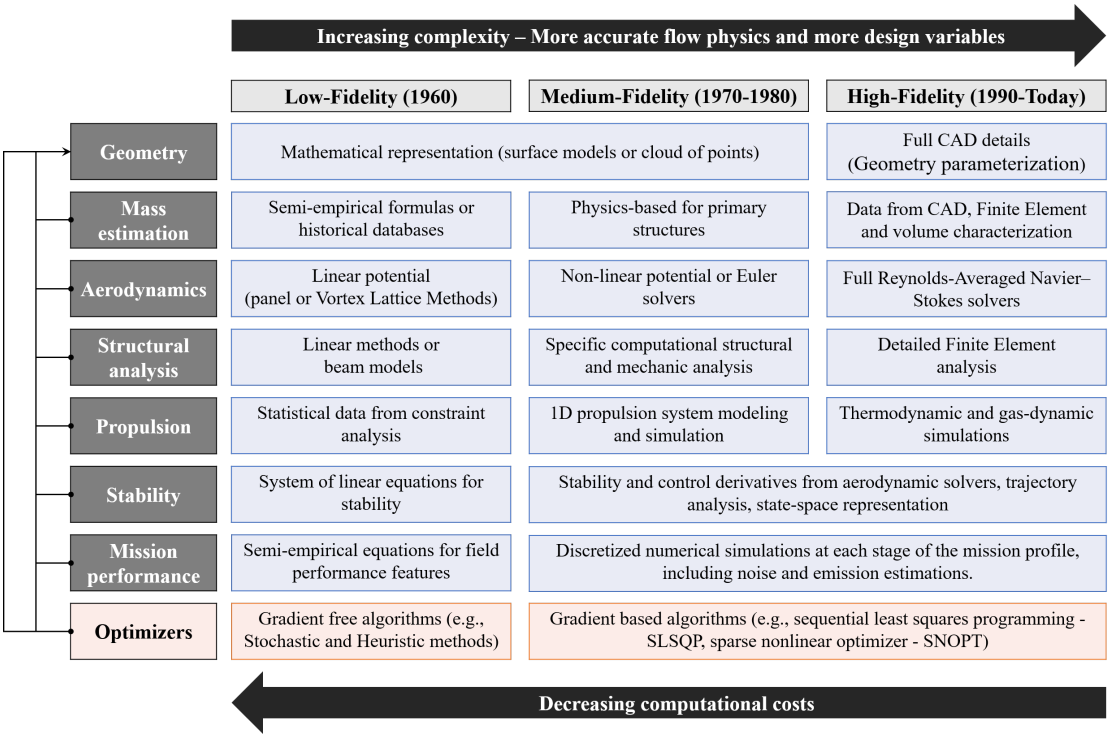


Figure 3: Hierarchy of MDO solvers with corresponding complexity and computational cost (created based on [111, 113, 114]).

provide a financial return for the operator. Therefore, new aircraft typically minimize a combination of DOC and Net Present Value (NPV), subject to meeting regulations. In this case, fuel consumption comes in through DOC, noise comes in through regulations, and emission reductions come via fuel-burn reductions and some regulatory pressure (ICAO's new CO_2 standard). Conversely, in academia and research institutes, more flexibility is given in the objective functions and design space, since these studies often have a longer-term focus such that higher fuel prices, carbon pricing, and additional regulatory pressure is anticipated. In any case, whether or not a technology is adopted by industry will ultimately be determined by its financial viability.

There are several entities worldwide actively involved in next-generation aircraft research, with a number of ideas put forward as potential successors for the current CTW aircraft [115]. Concepts like the SBW and TBW feature a very high aspect ratio wing and aim to reduce induced drag during cruise, while trying to keep the weight as low as possible. The coupling between aerodynamics and structures makes it challenging to design optimal concepts. However, they are based on current fuselage designs, representing a lower cost and risk than other concepts such as the BWB or the Flying-V concept. In particular, the latter concepts increase aerodynamic efficiency through exploiting many multidisciplinary effects which ultimately increase the wetted aspect ratio and reduce the weight while enabling an increased wingspan, and thus produce benefits in terms of both induced and viscous drag. However, a challenge with these concepts is the limited design experience and a larger uncertainty in, for example, structural mass estimation and stability behavior. Consequently, the predicted benefit and the confidence in that prediction must be higher for these concepts in order to justify the risk and investment needed from industry. Similarly, concepts like propulsive fuselage, distributed propulsion, hybrid-electric propulsion, among others, exhibit stronger interactions between the airframe aerodynamics and propulsion system, relative to CTW designs with podded engines, owing to the propulsor-airframe integration. Therefore, it is necessary to consider the challenges in manufacture, certifying the design, but also certifying the design process to reduce risks and integrate these new aircraft with current airport infrastructure to allow a straightforward operation [148].

Despite these limitations, which also represent an opportunity for future studies, there are potential technologies capable of competing with the current CTW configuration. IATA [149] reported the estimated fuel efficiency benefits of such technologies, including the technology readiness level (TRL) classification and the Entry into Service (EIS) [150, 151] (Table 1). Note that some unconventional configurations have the potential to improve fuel efficiency on the order of 30%, but fully-electric or hybrid-electric aircraft are likely to cover a large part of efficiency gains. Therefore, there is a strong desire to improve the efficiency of future aircraft by introducing new technologies and new design concepts.

This chapter highlights the primary characteristics and performance estimates of unconventional configurations that have the

Table 1
List of new technologies (2020-2050). The numbers mentioned below are based on the IATA - Aircraft Technology Roadmap to 2050 for Environmental Improvement[1] [149].

Group	Concept	EIS	TRL	Fuel efficiency benefits
Aerodynamics	Natural Laminar Flow	After 2020	8	5 to 10%
	Hybrid Laminar Flow Control	After 2020	7	10 to 15%
	Variable camber / control surfaces	After 2020	5	5 to 10%
	Spiroid wingtip	After 2020	7	2 to 6%
Propulsion	GE9X	2020	8	10% (GE90-115B)
	Advanced turbofan	2020	8	20% (Trent 700)
	Counter Rotating Fan	After 2020	3	15 to 20%
	Ultrafan	2025	7	25% (Trent 700)
	Ultra-High Bypass Ratio engine	2025	5	5 to 10%
	Boundary layer ingestion[2]	2035	3	10 to 15%
	Hybrid-electric aircraft[3]	2030-40	3	40 to 80%
	Fully-electric aircraft[4,5]	2035-40	2	up to 100%
Systems	Fuel cells	2020	8	1 to 5%
	Electric taxiing system	2021	8	3%
Unconventional configurations	Strut- / Truss-Braced Wings[6]	2030-35	3	30%
	Box-wings[6]	2035-40	3	30%
	Morphing airframe	2040	3	5 to 10%
	Double-bubble aircraft[2,6]	2045	3	30%
	BWB / HWB[7]	2045	3	27 to 50%
Materials/Structures	Lightweight cabin interior	Retrofit		1 to 5%
	Structural health monitoring	Retrofit		1 to 4%
	Advanced materials	Production Upgrade		1 to 3%
	Active load alleviation	Production Upgrade		1 to 5%
	Composite primary structures	Production Upgrade		1 to 3%
	Composite secondary structures	Production Upgrade		$< 1\%$

[1] TRL and EIS are subject to substantial changes due to technological progress and COVID-19 crisis [3].
[2] Coupled with distortion tolerant fans.
[3] Depending on battery use.
[4] Primary energy from renewable source.
[5] Only for short range.
[6] With advanced turbofan engines.
[7] With hybrid propulsion.

potential to meet the most demanding requirements in terms of fuel reduction by enhancing the aerodynamic performance through the implementation of different technologies. However, according to the last independent expert integrated review panel, unconventional configurations are unlikely to be operational before 2037 [148].

4.1. Blended/Hybrid Wing Bodies

The BWB concept is one of the most promising unconventional configurations, providing several different benefits over CTW aircraft. In this design, the shape of the aircraft fuselage is modified so that it can contribute to the generation of lift, i.e., the fuselage and wings are blended together, and the empennage is mostly eliminated, creating a single lifting body, which offers major reductions in terms of interference drag and wetted area, increasing the aerodynamic efficiency and making available additional space in the cabin to increase passenger and cargo capacity. The BWB also enables better alignment of the lift and load distributions, thereby reducing bending moments. This enables a longer wingspan, which provides an induced drag benefit.

The earliest publications about BWB configurations are those by Robert Liebeck [152, 153] and Rodrigo Martínez-Val [154, 155]. Liebeck is recognized as one of the pioneers of the BWB configuration. His main contribution was the conceptual design of a double deck BWB that has been extensively studied by using high-fidelity CFD and wind tunnel tests. It is an 800-passenger BWB designed for flying 7000-n mile, which presented a 15% reduction in take-off weight and 27% reduction in fuel-burn per seat mile over a CTW aircraft of equivalent engine and structural (composite) technology for a 2010 entry into service. On the other hand, Martínez-Val reported some of the first conceptual design studies of a BWB configuration for 300 passengers, highlighting its prospects and challenges in subjects such as airport capacity, community noise, air space capacity, and emissions. Besides

Figure 4: X-48B Blended Wing Body (source from [162]. Credits: NASA / Carla Thomas).

these significant contributions, Bolsunovsky et al. [156], Okonkwo and Smith [157] and Zhenli et al. [158] developed complete literature reviews about the progress of the BWB configuration, from historical conceptions and challenges, to future developments and applications. Likewise, Liou et al. [159] summarized the contributions of NASA considering high-fidelity capabilities for designing advanced HWB configurations, specifically on HWBs with embedded engines.

In the past, the BWB design was mainly conceived for military purposes such as the Northrop B-2 bomber. However, in civil aviation, the BWB configuration has always been seen as a typical example of a futuristic aircraft which could enter service over the next few decades. Scientists from NASA, Boeing, Airbus, DLR, among others, have been working on their next generation airliner, testing BWB concepts for future commercial purposes. To explore its aerodynamic capabilities as well as stability and control and handling properties, some experimental unmanned subscale concepts, such as the X-48 (shown in Fig. 4), and the MAVERIC concept have been manufactured and tested with a blended-wing design. In case of the X-48, flight tests showed that the aircraft was quieter than expected, and had a better fuel efficiency when flying with a greater payload weight [160]. Likewise, the MAVERIC flew for the first time in June 2019, showing the potential to reduce fuel consumption by up-to 20% compared to current single-aisle aircraft [161].

So far, the BWB configuration has been studied in many universities, companies, and government labs, mainly developing conceptual designs for different mission profiles. The major different BWB versions are summarised in Tables 2, 3, and 4 and are discussed next. The configurations are arranged by the level of fidelity of the design and analysis tools used, highlighting the main performance characteristics, as well as fuel-burn benefits over their CTW counterparts. The following observations can be made:

- According to the mission profile, level of fidelity and top-level requirements proposed for each mission, BWB concepts have demonstrated higher ML/D values than existing CTW aircraft, which are mostly in the range of 15, assuming current technology levels [205]. This variable represents the most important metric for assessing aerodynamic performance, so the high values obtained by each BWB concept can imply a reduction in cruise fuel-burn, which can be translated into DOC savings relative to CTW concepts. In particular, the high aerodynamic performance comes from large mean aerodynamic chord and high wetted aspect ratio, although more improvement can be expected by adopting advanced technologies, as in References [165, 173, 191, 195, 203], whose fuel-burn benefits are remarkable in comparison with CTW aircraft.
- Key technical aspects identified in early studies demonstrated that BWB concepts can reduce noise by shielding the propulsion system, providing an adequate space for installing distributed propulsion or BLI engines [153, 177]. As a result, multiple MDO formulations, mostly medium-fidelity frameworks, were used to investigate the implications of next-generation propulsion technologies on BWB concepts, as shown in Table 3. In general, the primary benefit of BWBs with BLI is an overall improved system efficiency over podded engines, including reductions in ram and viscous drag, and propulsion integration weight. In order for the overall system efficiency benefit to be realised, challenges to be addressed include the need for careful inlet design to minimize distortion and pressure losses [206] and distortion-tolerant fans [207]. Even with such challenges, particular concepts such as SAX-40 [176], and N3-X [178] demonstrated that up to a 15% reduction in fuel-burn can be achieved.
- The early studies focused on large capacity (400 to 800 passengers) and long range (up to 6000 nm) BWBs, showing a clear benefit in terms of payload range efficiency and fuel efficiency per seat when compared to conventional reference aircraft. Scaling studies, such as those reported by Nickol et al [190, 191], confirmed those findings, demonstrating that typical BWB configurations do not provide enough fuel-burn savings for smaller transport aircraft, because the magnitude of the potential

Table 2: Summary of BWB/HWB concepts using low-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Wakayama and Kroo [163] / 1998	7500	35000	855	0.85	-	-	Conceptual design studies and cabin layout optimization using both gradient-based and genetic algorithms.
Bradley [164] / 2004	7750	39000	450	0.85	-	-	A sizing methodology for the conceptual design of BWB configurations. The implemented methodology allowed to represent the trade-off between minimum thickness and planform cabin area.
Martinez-Val et al. [165] / 2007	5400	45000	300	0.8	-	38	Conceptual design of a C-type flying wing using laminar flow control, vectored thrust, and active stability.
Dommelen and Vos [166] / 2014	6000	36000	400	0.82	22.8	-	This paper reported three different BWB configurations at conceptual design level. Data for BWB with aft-swept wings with aft-mounted engines and winglets doubling as vertical tails.
Okonkwo [167] / 2016	7620	36000	555	0.85	17.3	-	This thesis provides a complete low-fidelity framework for MDO of BWB configurations.
Ammat et al. [168] / 2017	2354	35000	200	0.82	18.8	-	Conceptual design of a BWB concept including performance and dynamic stability studies.
Brown and Vos [169] / 2018	3922	35000	250	0.8	17.5	22	Conceptual design methodology for BWB concepts within a semi-automatic design environment. This paper included data for other BWBs with different payload requirements.
Centracchio et al. [170] / 2018	900	25000	100	0.5	9.5	-	ARTEM BWB - a hybrid electric high-capacity regional BWB aircraft. This project involves the development of efficient models for the aeroacoustic assessment of this class of aircraft.

Table 3: Summary of BWB/HWB concepts using medium-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Ko et al. [171] / 2003	7750	36500	478	0.85	25.5	-	This research reported an MDO for a BWB with distributed propulsion. Subsequent works included duct modeling within the optimization algorithm [172].
Daggett et al. [173] / 2003	3000	-	468	0.85	-	42	BWB 450-1U airplane. Fuel-burn benefits from BLI and active flow control.
Liebeck [153] / 2004	7000	35000	800	0.85	18.4	27	Conceptual and preliminary design of a BWB configuration. This article discusses potential effects of BWB on air transport. Fuel-burn benefits from equivalent technology levels.
Qin et al. [174] / 2004	7500	38000	800	0.85	20.1	-	Aerodynamic considerations of BWB design. The optimized BWB geometry provided an overall drag reduction of 9% against a baseline BWB. This study was limited to aerodynamic and trim considerations.
Hansen et al. [175] / 2006	7667	35000	750	0.85	17.8	-	VELA project was created to develop design tools for a very efficient large BWB aircraft concept.
Hileman et al. [176] / 2010	4500	45000	335	0.8	20.1	28	SAX-40 concept (Silent Aircraft eXperimental). This aircraft meets the noise requirements relative to the ICAO chapter 4. An MDO framework that assessed the benefit of BLI inlets can be found in [177].
Felder et al. [178, 179] / 2009, 2011	7500	35000	300	0.8	-	25	The N3-X HWB concept employs turboelectric distributed propulsion which utilizes superconducting electric generators, motors, and transmission lines. Specific details of several disciplines can be found in [180, 181, 182, 183, 184, 185].
Kawai [186] / 2011	6000	35000	375	0.8	-	25	Efficient low-noise HWB concepts (N2A and N2B) designed by Boeing. They are expected to offer significant benefits in noise reductions without compromising the fuel-burn. Highlights on duct modeling and BLI optimization can be found in [187].
Peifeng et al. [188] / 2012	7300	36000	300	0.83	17.4	13	NPU-BWB-300 concept. This research focused on aerodynamic characteristics using equivalent levels of technology. Subsequent studies involved nacelle-airframe integration [189].
Nickol [190] / 2012	7500	35000	301	0.84	19.7	6	This study investigated the question of HWB fuel-burn performance as a function of size. Data for a 300-pax Jetliner HWB based on the ERA project; other HWB categories and scaling studies were evaluated.
Nickol and Haller [191] / 2016	6600	35000	216	0.8	24	45.3	Conceptual design and analysis of advanced subsonic commercial transport concepts. Data for a small twin aisle HWB concept; other versions such as very large twin aisle HWB concepts were also evaluated. Fuel-burn benefits relative to a 2005 best-in-class CTW aircraft.
Dorsey and Uranga [192] / 2021	3000	36000	200	0.78	18.9	14.8	This study focused on design space exploration of BWBs. Data for a 200-pax single deck BWB; other categories and double deck BWB configurations were also evaluated.

Table 4: Summary of BWB/HWB concepts using high-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Bradley and Droney [97] / 2011	3500	35000	154	0.8	-	43	HWB from SUGAR program. This aircraft enables NOx reduction of 28% compared to CTW aircraft.
Kuntawala et al. [193] / 2011	6000	41000	12	0.85	18.2	-	Aerodynamic shape optimization of a BWB configuration using an Euler-based approach. The optimized geometry reduced drag by about 38.7% compared to a baseline BWB geometry.
Lyu and Martins [194] / 2014	7000	35000	800	0.85	18.5	-	High-fidelity aerodynamic optimization of a BWB using a multipoint approach, subjected to trim, static-stability, and root-bending-moment constraints.
Isikveren et al. [195] / 2015	4800	41000	340	0.8	21.2	37	HWB with distributed propulsion and ultra-high by-pass rotors. Concept from DisPURSAL Project.
Reist and Zingg [196] / 2016	500	46000	105	0.78	$17.9_{@HWB}$ $18.7_{@LFC}$	-	High-fidelity aerodynamic optimization of an HWB and a narrower version called the lifting fuselage concept (LFC). This work showed that HWBs with narrow-centerbodies offer superior aerodynamic performance compared with classical BWBs in the regional class.
Prakasha et al. [197, 198] / 2018	4589	43000	450	0.8	-	-	HWB designed by DLR in AGILE-paradigm. This is a long-term project that focuses on BLI and distributed propulsion.
Yang et al. [199, 200] / 2018	3600	35000	120	0.8	-	30	Single-aisle airliner with a single-deck BWB (Ascent 1000 BWB from DZYNE Technologies). Fuel-burn benefits from the combination of light structures, and a low drag design.
Reist et al. [201] / 2019	2000	36000	100	0.78	16.2	-	Multi-fidelity and multidisciplinary optimization of HWBs with narrow centerbodies, involving stability and control requirements. Data for HWB with fin-equipped; other versions such as winglet-equipped were also evaluated.
Sgueglia [202] / 2019	2750	35000	150	0.78	17.8	13.2	Multidisciplinary optimization of a BWB with distributed electric propulsion. Results have been compared to a conventional A320 aircraft based on the same top level requirements.
Karpuk et al. [203] / 2020	8099	35000	300	0.8	27.2	60	Multi-fidelity design of a long-range BWB. This particular concept involved advanced structural design with the integration of active flow control, active load alleviation and boundary layer ingestion with ultra-high bypass ratio turbofan engines.
Gray et al. [204] / 2021	2000	36000	100	0.78	17.8	-	This work is a further exploration of HWBs with narrow-centerbodies including more demanding flight constraints. The optimum result burned 11.2% less fuel than a baseline HWB.

Figure 5: Dzyne Technologies' regional-sized BWB design concept (source from [209]. Credits: NASA/DZYNE Technologies/Brendan Kennelly).

fuel-burn benefit is a function of payload and design range. For example, a 98 passenger configuration burned more fuel (+4%) than a comparable CTW aircraft. Conversely, a 300 passenger configuration burned less fuel (−6%) than its CTW counterpart. A simple geometric analysis shows that the ratio of wetted area to floor area increases as the size of the BWB aircraft decreases, and hence the wetted aspect ratio is reduced for smaller BWBs [208]. Therefore, high-fidelity aerodynamic shape optimization has been applied to new regional-class HWBs, as a potential method to obtain suitable drag reductions [196, 201] (see Table 4). These studies all come to the same result: HWB concepts for regional-class aircraft appear more like a narrow body with a distinct wing, offering a greater level of performance than a blended wing concept. Finally, a more recent effort showed that through design space expansion within a framework encompassing high-fidelity flow physics, the HWB was shown to be more efficient despite being required to satisfy low-speed trim and static margin constraints [204].

Based on the above tables and discussion, we can infer that many organizations are seriously considering the BWB/HWB technology as a potential commercial venture. These concepts clearly provide a set of environmental and financial benefits that are appealing for next-generation civil aviation, such as increased cargo capacity at lower fuel-burn, which is critical for airline businesses because any fuel savings will benefit DOC. Nevertheless, several potential issues still require extensive research and development efforts. For example, large cabins imply new operational procedures to satisfy cabin safety requirements, such as new evacuation plans and load paths. Furthermore, passenger comfort problems in a roll maneuver may occur if they are sitting far away from the centerline. Another issue is related to incompatibilities with the existing airport infrastructure, such as gates height and ground facilities. Finally, as the cabin hull is not cylindrical, structural problems may occur due to internal pressurization loads.

Although many of these challenges have been addressed on the DZYNE's Ascent1000 concept (Fig. 5), it involves major technological innovations unproven in any operating aircraft, such as the pivot-piston main-gear required for takeoff rotation, the structural advantages of PRSEUS panel construction, and the T-plug family-oriented manufacturing concept [199, 200]. The interactions among these novel technologies, introduced simultaneously, also increase the risk. However, DZYNE's Ascent1000 design is the aircraft with the greatest accomplished TRL among others in the same category, providing significant noise reduction, increased safety, increased comfort, and faster and safer turnarounds with gate systems.

4.2. Box-Wings

The BW configuration features a close non-planar wing that has been extensively studied since Prandtl invented the "best wing system" in 1924 [210]. According to Prandtl, the best wing system is a box-wing that could reach much lower values of induced drag than equivalent monoplanes that have the same wingspan and lift. Such a theoretical foundation introduced the concept, and led to several efforts that have been focused on studying the induced drag problem in non-planar wings and their optimal lift distribution. For example, Kroo [211] implemented a low-fidelity approach for assessing the aerodynamic properties of non-planar wings, demonstrating that box-wings decrease induced drag by allowing for span efficiencies greater than unity. Later, Frediani and Montanari [212] studied the box-wing system assuming that the lift is equally distributed on the fore and aft wings, forming a butterfly-shaped distribution on the vertical tip fins. However, Demasi et al. [213] later showed that the distribution of optimal aerodynamic load/circulation over box-wings does not follow an elliptical law. Indeed, the actual solution has a shape that changes from quasi-elliptical for zero gap between the wings, to a constant distribution when the wings are extremely distant from each other [214, 215]. Modern computational aerodynamics has provided an additional perspective, demonstrating a strong correlation between numerical results and Prandtl's prediction [216, 217].

Figure 6: Lockheed Martin's box-wing concept for the N+2 study (source from [223]. Credits: NASA/Lockheed Martin).

Later conceptual design studies, at different levels of fidelity, have concluded that box-wings offer superior performance than conventional wings, without exceeding airport span constraints or deviating dramatically from the CTW concept. Furthermore, recent studies have shown that the structural features of a closed wing system might contribute to a reduction in wing weight [218, 219], increasing reliability on the basis of a deep risk analysis for future development.

Comprehensive reviews about non-planar wing configurations are given by Cavallaro and Demasi [220], Wolkovitch [221] and Buttazzo and Frediani [222]. These publications discuss the design challenges and innovations of a variety of non-planar wing configurations, covering different engineering areas such as aerodynamics, structures, aeroelasticity, and stability and control. Therefore, some current projects have focused on examining the multidisciplinary interaction of those disciplines, in order to improve vehicle and system-level efficiency.

In this context, the first in-depth conceptual investigation was reported by Lange et al. [224], under a NASA contract in co-operation with the Lockheed Martin company. This project intended to improve the aerodynamic performance and enhance the payload capacity of a 400 passenger aircraft. Several configurations were explored and studies concerned both aerodynamic and structural aspects. Parametric studies revealed the optimum sweep combination for minimum drag is 45^o forward-wing sweep and -30^o aft-wing sweep. This arrangement provided a 30% lower induced drag than its CTW counterpart while retaining longitudinal stability constraints. The rest of the project was devoted to meet flutter criteria, which revealed that symmetric and antisymmetric modes occur below the required flutter speed. A more recent update of this project is the box-wing concept for the NASA ERA N+2 studies (Fig. 6). In this particular case, the aircraft features Hybrid Laminar Flow Control (HLFC), an advanced turbofan engine, and a fully composite structure [223]. Even with proven technology, this configuration requires further optimization, in order to find the best compromise among the entire characteristics of the aircraft.

Following this effort, a large number of research projects are still being explored, demonstrating that the deployment of the BW concept as a next-generation aircraft can provide a long-term solution to the growing demand of air passengers in the future decades. In particular, the University of Pisa is developing the research project called PARSIFAL (Prandtlplane architecture for the sustainable improvement of future airplanes), which is funded by the European Union under the Horizon 2020 program and intends to enter service in the 2030s (Fig. 7). Frediani et al. [225] presented the PrandtlPlane configuration in a review paper, summarizing motivations, possible applications, and experience gained in more than a decade of studies on the topic. The experience gained in PARSIFAL contributed to the conceptual development of BW aircraft of various categories, such as business jets and hybrid electric regional aircraft. Some of the main challenges along with general possible solutions can be found in [226]. A large effort was the development of the IDINTOS project. This configuration is an ultralight amphibious PrandtlPlane, which was designed and manufactured as a technology demonstrator in order to study the advantages of a box-wing design over conventional configurations. The main technical data can be found in [227, 228]. In this study, two main advantages have been observed. First, the fore wing stalls first so that the aft wing introduces a significant negative pitching moment that keeps the aircraft away from the stall conditions. Furthermore, since the two wings are placed at a considerable distance from the center of gravity, the pitch damping moment is higher than in a conventional aircraft; thus, the longitudinal stability is improved. Such features along with various ongoing research activities have enabled other design perspectives, such as future urban air mobility configurations [229, 230].

Major design studies by academia, research centers, and industry are listed in Tables 5 and 6. Different levels of fidelity, as well as payload and range capabilities are highlighted, and some of the main conclusions are as follows:

- Overall, low-fidelity BW designs (Table 5) show a lower induced drag and a lower fuselage weight due to distributed bending loads than their CTW counterparts. Some minor differences were seen, depending on the aircraft category. For example, for single-aisle - medium-range missions, the authors found fuel-burn benefits of about 7% considering a maximum payload. However, more significant gains are obtained by long-range mission aircraft, where the low induced drag can produce a 10% saving on fuel-burn. Some studies demonstrate that high-payload BW aircraft can handle existing airport constraints such as take-off and landing lengths, as well as wingspan limitations imposed by gate restrictions. Despite these exciting findings,

Table 5: Summary of Box-Wing concepts using low-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Lange et al. [224] / 1974	5500	37000	400	0.95	-	-	"Interim" configuration of the transonic Box-Wing studied at Lockheed in the 1970s. The results showed that a transonic BW may have the same gross weight and superior fuel efficiency than a conventional reference.
Khan [231] / 2010	3100	37000	189	0.78	18.6	-	The BW configuration reduced the induced drag by about 18% compared to CTW aircraft.
Schiktanz [232] / 2011	1550	42300	150	0.78	15.9	9	Conceptual design of a BW aircraft using semi-empirical approaches. This research looked into a variety of subjects, with a focus on the flying qualities of the aircraft.
Jemitola [233] / 2012	4000	36000	270	0.79	17.1	7	Conceptual design of a BW aircraft. An empirical equation for the mass estimation of the fore and aft wings was derived [234].
Beccasio et al. [235] / 2012	2500	29000	250	0.75	12.3	-	Conceptual design of a BW aircraft powered by liquid hydrogen. The optimum aspect ratio and cruise altitude were determined as a trade-off between high performance and low environmental effects.
Zohlandt [236] / 2016	2160	37000	144	0.78	14.1	8	Conceptual design of high subsonic Prandtlplanes. Data for single aisle - medium range aircraft; other categories were evaluated.
Garcia-Benitez et al. [237] / 2016	6000	35000	250	0.82	18.5	-	Conceptual design of a non-planar wing concept. The best configuration increased range by about 17% compared to a CTW aircraft.
Kaparos et al. [238] / 2018	2160	35000	180	0.78	-	-	Conceptual design of a BW aircraft using semi-empirical approaches and some CFD analysis for validation.
Bravo-Mosquera et al. [239] / 2019	1000	41010	160	0.78	14.2	12	Conceptual-level MDO of a BW aircraft coupled to a BLI system. Wind-tunnel experiments and high-fidelity optimization studies continue to be developed.

Table 6: Summary of Box-Wing concepts using medium-fidelity and high-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Salam and Bil [240] / 2016	1000	35000	150	0.7	-	5	Multidisciplinary analysis of a BW aircraft using low-fidelity aerodynamics and a finite-element method for structural analysis.
Andrews and Perez [218] / 2018	1540	37000	86	0.74	12.6	1.2	Multidisciplinary analysis of regional-jet BW aircraft. Novel models for predicting static longitudinal stability and structural weight were developed [241, 242].
Frediani et al. [243] / 2019	2160	36000	320	0.79	16.2	20	PARSIFAL (Prandtlplane Architecture for the Sustainable Improvement of Future Airplanes). Results of this investigation demonstrated an increase in payload capability of 66% and a reduction in fuel consumption per passenger km up to 22%, in comparison with a conventional reference. The authors have also reported aerodynamic optimization [244], performance [245], stability [246], structural [247], and emissions [248] analyses.
Ciampa et al. [144] / 2019	1943	36000	150	0.78	-	5.5	BW concept from AGILE project. The study focuses on the impact of the fuel trim system on the stability and control qualities of the vehicle.
Gagnon and Zingg [249] / 2016	500	36000	100	0.78	-	-	Aerodynamic trade-offs of a BW concept using an Euler-based approach. Induced drag was reduced by 43% compared to its CTW counterpart. This study did not include wing-body flow interactions.
Chau and Zingg [250] / 2017	600	36000	100	0.78	13.9	7.6	RANS-based aerodynamic shape optimization of a regional-class BW concept.

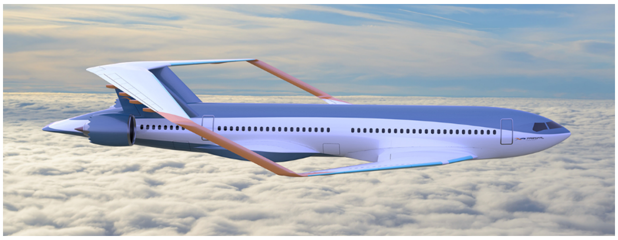


Figure 7: PrandtlPlane from PARSIFAL project (source from Salem et al. [118]. Credits: Pisa University).

some of these studies lack an effective optimization method and thus need more comprehensive research to achieve more reliable estimates of the potential benefits of this configuration.

- More recently, multidisciplinary studies of BW configurations allowed a deeper understanding of the trends leading to a reduction in fuel consumption for transport aircraft (Table 6). The main results demonstrated that the BW aircraft achieves a higher lift-to-drag ratio (L/D) at cruise, indicating superior performance in terms of cruise fuel burn over CTW aircraft. However, estimating the wing mass has been a significant challenge, and different methods have been used to obtain an acceptable level of accuracy, ranging from semi-empirical relations based on statistical data [234], beam finite element models [218], and structural surrogate models [247]. Although the BW can have a lower span than a CTW aircraft designed for the same mission, it can require a larger planform area if the fuel is stored in the wings, increasing the skin-friction drag, and wing weight [218]. This gives the CTW aircraft an advantage over BW designs in terms of operational empty weight and maximum takeoff weight, reducing fuel consumption in take-off and climb. The distribution of fuel in the wings presents a design challenge. A potential solution is to hold a large volume of fuel inside the fuselage; however, this still requires extensive research efforts and introduces certification challenges. Finally, these BW concepts share specific design characteristics such as a rear installation of the engines and fuselage-mounted main landing gear, which increase fuselage weight, as well as cost and integration complexity.
- There are a few works focused on high-fidelity optimization of BW concepts [249, 250]. Such works provided a more detailed perspective about its benefits in terms of the geometric arrangement. For example, the area allocation between the fore and aft wings provides a unique capability to the BW to redistribute its optimal lift distribution. Since the two wings are placed at a considerable distance from the center of gravity, the pitch damping moment is higher than in a CTW aircraft; thus, trim and other design constraints can be satisfied without performance reduction. Such studies focused solely on the wing geometry, therefore, more detailed information about the actual performance of a BW concept can be obtained if the fuselage is included in the aerodynamic optimization loop. This subject is being analyzed on the INTI aircraft [239]; results will be reported in future publications.

Although the practical benefits of the BW configuration can only be proved in a detailed design study, the concepts reviewed in this article demonstrated the potential for fuel-burn reduction and the importance of adopting a multidisciplinary design approach. In this regard, many areas require further study. For example, through the viewpoint of flight dynamics, unconventional control surfaces may cause a more complex dynamic behavior. Therefore, CFD and wind-tunnel experiments are required to evaluate the dynamic derivatives, since empirical methods do not provide accurate results. Even though there is a recent study about the mission performance of a BW aircraft in low-speed conditions [251], high-lift devices still require high-fidelity analysis, in order to evaluate the actual behavior on the different flight phases of a transport mission.

Moreover, the aft wing of the BW configuration may suffer different types of aeroelastic instabilities, such as divergence due to its negative sweep angle [252], and flutter, in which a dual-fin assembly is the most promising solution [225]. Some researchers have studied challenges and opportunities associated with dynamic aeroelasticity and the structural nonlinearities on the Prandtlplane aircraft [253, 254]. The authors demonstrated that its particular distribution of stiffness, along with its dual-fin configuration, prevents physical instability. The relevance of considering the vehicle's elasticity while evaluating its flying qualities is further highlighted by the authors. It is important to note, however, that the dual-fin configuration increases the structural weight and may be prone to shock formation and interference drag. Thus, their viability remains a challenge in a full-scale concept. As such, aerostructural optimization can provide a more detailed understanding of the effects of structures on weight and the entire aerodynamic performance. Finally, further research on the BW aircraft's manufacture is necessary, in order for industry to take on the development cost and risk of this configuration.

4.3. Strut- and Truss-Braced Wings

Since 1950, the SBW configuration has been studied to evaluate its feasibility and potential. The SBW configuration enables a substantial span increase, while potentially reducing the structural weight, thereby decreasing induced drag to yield a significant fuel-burn benefit. The idea of using an SBW for a long-range transonic transport aircraft was first proposed by Pfenninger in the early 1950s [255]. Other pioneering SBW studies were performed at NASA and Lockheed [256, 257], demonstrating that SBW concepts with high aspect ratio wings can improve cruise range when compared to a same baseline concept.

Likewise, the TBW emerged due to the potential benefits of the SBW. The main difference is that TBW concepts have a strut and jury members connecting the strut and the main wing, enabling the aspect ratio to be further increased. However, longer wings are subject to flutter, so trusses are used to alleviate this phenomenon. Such a configuration results in a significantly larger design space, since truss members require additional design variables to account for the size and shape of each member in the truss. Therefore, the two primary challenges faced by SBW and TBW concepts are flutter and shock waves in junction regions and in the "channel" formed by the strut. Buckling is also a design challenge for the SBW, since the strut is compressed during negative load conditions, and the inboard wing segment is compressed during positive load conditions, resulting in increased weight penalties [129]. This is generally true for all joined wing systems, including box wings, which are statically indeterminate structures. It is important to note that the main challenges in terms of aerodynamic and structural nonlinearities represent a design opportunity, since detailed design and certification require more accurate procedures [220].

Grasmeyer [258] investigated the benefits of SBW concepts over advanced CTW aircraft. The optimum configuration showed a 15% reduction in takeoff gross weight, a 29% reduction in fuel weight, a 28% improvement in L/D ratio, and a 41% increase in seat-miles per gallon. Since this work, several MDO methods have been developed to study the design characteristics of SBW and TBW configurations. Tables 7, 8, and 9 summarise major design studies by academia, research entities, and industry arranged by level of fidelity. The main design and performance characteristics are as follows:

- The most important outcomes show the advantage of strut and simple truss configurations over CTW cantilever aircraft in terms of fuel-burn. The high wingspan of these concepts, which can be vulnerable to aeroelastic phenomena, pose significant structural and aerodynamic uncertainties in the early studies. However, most recent medium fidelity frameworks expanded their capabilities by considering the extent of laminar flow on the wings, fuselage relaminarization, structural characteristics, the influence of supercritical airfoils on the wing-strut intersection and the effects of flutter (Table 8).
- SBW and TBW concepts demonstrate higher ML/D values than CTW counterparts. This is an anticipated outcome, since these concepts have higher aspect ratio wings and are designed to operate at higher cruise altitudes than conventional aircraft. Furthermore, the studies reported different design approaches in terms of objective functions, design constraints and technological feasibility. For example, some aircraft used a set of aerodynamic considerations for reducing skin-friction drag such as fuselage relaminarization, surface riblets, and tailless arrangements, which increased the ML/D values substantially. Such configurations present optimistic ML/D values, as a result of the inclusion of aggressive technologies. Conversely, some aircraft are constrained by the effects of flutter, and also penalized by interference drag. Therefore, there is a discrepancy in the stated values.
- A few efforts have looked into aerodynamic shape optimization to study the aerodynamic interactions between SBW surfaces (e.g., reduction of shocks and separation in the wing-strut junction). Gagnon and Zingg [271] performed an Euler-based aerodynamic shape optimization on several unconventional configurations (see Fig. 8), enabling comparison of four distinct configurations. The authors designed and optimized a BW, a C-tip BWB, and an SBW concept for the same regional mission (similar to the Bombardier CRJ-1000) and subjected to the same problem formulation. The SBW configuration obtained the least amount of drag (-40.3%) relative to an equivalently optimized CTW, followed by the C-tip BWB (-36.2%), and finally the BW (-34.1%). Such results demonstrate the high potential of the SBW configuration relative to other unconventional configurations. Nevertheless, RANS-based optimization is needed to increase the confidence in these comparisons. Recent efforts, demonstrate that aerodynamic shape optimization is effective in eliminating shocks at the wing-strut junction using a RANS-based approach, in particular, Secco and Martins [274] at low Mach numbers using the PADRI SBW geometry [276], and Chau and Zingg [129] at more conventional transonic Mach numbers (regional-class aircraft).

There has also been progress on aerodynamic and structural characteristics since 2008 in the SUGAR program under NASA and Boeing sponsorship [97, 98, 99, 100, 101]. During phase I, researchers selected baselines and advanced configurations, conducted performance analyses, and measured noise and emissions. Additional technologies such as liquefied natural gas, hydrogen, fuel cell hybrids, BLI propulsion, unducted fans, and advanced propellers were evaluated in phase II. Phases III and IV focus on improving the maturity of CFD models and experimental campaigns in order to facilitate industry adoption of transonic TBW technology, i.e., the objective is to identify remaining technical and certification challenges and develop a roadmap for the continued systematic reduction in risk [278, 279]. An aircraft example from SUGAR program is the SUGAR Volt (Fig. 9), that has been optimized under several aeroelastic constraints before being validated in high-speed wind tunnel tests. This particular concept also involves critical technologies such as hybrid electric propulsion, and high rate composite manufacturing, promoting a radical fuel-burn reduction of 63.4% compared to a 2020 in-production aircraft, thus demonstrating that a high ML/D and lighter materials enable much greater range for a given battery energy density, as stated by Bushnell [280].

As described in this section, many studies have been conducted to explore the potential of SBW and TBW in a multidisciplinary manner. The following aspects highlight the main advantages of such configurations: (i) SBW and TBW concepts provide a bending load alleviation to the wing, allowing for a decreased thickness to chord ratio, and consequently, a reduction of wing weight and

Table 7: Summary of SBW and TBW concepts using low-fidelity tools.

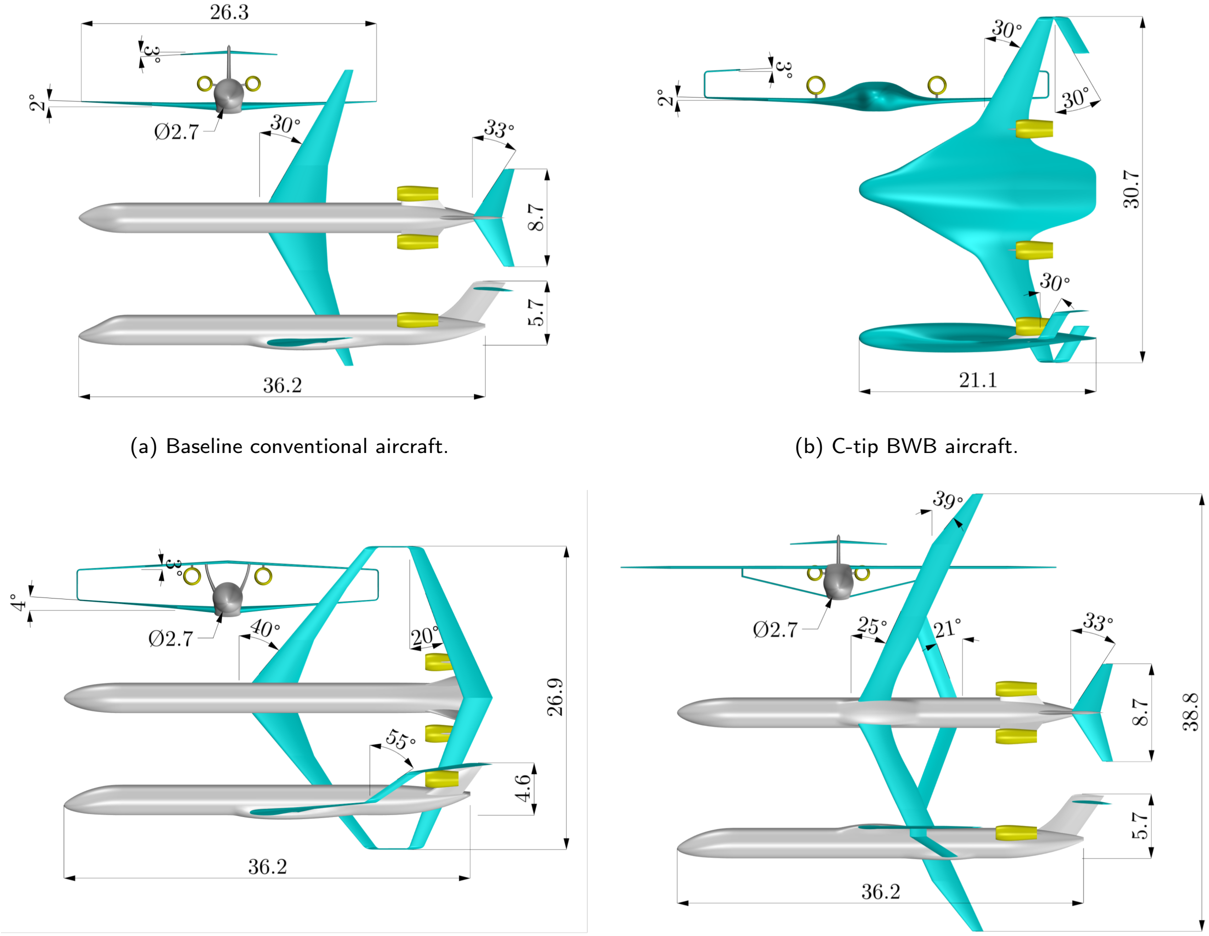
References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Grasmeyer [258] / 1999	7380	39432	305	0.85	23.3	29	MDO of several SBW concepts, including advanced technologies such as Natural Laminar Flow (NLF) and relaxed static stability to increase performance. Fuel-burn benefits over a 1995 technology aircraft.
Gundlach et al. [259] / 2000	7500	42300	325	0.85	21.6	13.6	Conceptual design of an SBW concept focused on takeoff gross weight reduction. Data for fuselage-mounted engines, and performance benefits given for a 2010 service entry date aircraft.
Gur et al. [260] / 2010	7730	$47000_{@SBW}$ $48000_{@TBW}$	305	0.85	$21.2_{@SBW}$ $21.2_{@TBW}$	$3.9_{@SBW}$ $8.8_{@TBW}$	Single objective optimizations of SBW and TBW concepts at different levels of technology. Three objective functions were studied: minimum takeoff gross weight, minimum fuel consumption, and maximum L/D ratio. Data for minimum-fuel objective and current technology levels.
Gur et al. [261] / 2011	7730	48000	305	0.85	$22.8_{@SBW}$ $27.9_{@\frac{TBW}{1-jury}}$ $29.4_{@\frac{TBW}{2-jury}}$	$8.6_{@SBW}$ $18.1_{@\frac{TBW}{1-jury}}$ $19.8_{@\frac{TBW}{2-jury}}$	MDO of SBW and TBW concepts assuming aggressive laminar flow on wings, fuselage, and fairing. Fuel-burn benefits are given for three distinct configurations at the same level of technology of a CTW counterpart.
Gur et al. [262] / 2011	7730	48000	305	0.85	$31_{@0.01}$ $36.5_{@0.5}$ $38.2_{@0.75}$	- - -	MDO of TBW concepts (2-jury struts). This work focused on several drag-reduction technologies into the optimization loop such as fuselage relaminarization, surface riblets, tailless arrangements, and Goldschmied propulsion apparatus.
Hosseini et al. [263] / 2020	1240	20000	72	0.5	9.6	9.6	Conceptual design of a TBW concept for regional missions. This work involves medium fidelity aerodynamics and low order mass estimation methods.

Table 8: Summary of SBW and TBW concepts using medium-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Gern et al. [264] / 2001	7500	42300	325	0.85	25.1	12.2	MDO of an SBW using a refined aerodynamic module by using CFD simulations and a structural module to evaluate the aerodynamic loads. Data for fuselage-mounted engines and minimum fuel weight objective; other categories, objective functions and engine location were evaluated.
Meadows et al. [265] / 2012	3115	$45700_{@SBW}$ $48800_{@TBW}$	162	0.78	$28_{@SBW}$ $30.3_{@TBW}$	$8.5_{@SBW}$ $9.2_{@TBW}$	MDO of SBW and TBW concepts. This work focused on engine installation (wing and fuselage) assuming advanced aerodynamic technology levels. Fuel-burn benefits are given for wing-mounted engines at the same level of technology of a CTW counterpart.
Chakraborty et al. [266] / 2015	3500	45000	154	0.7	-	-	MDO of SBW and TBW concepts (1-jury) using NLF technologies. The TBW with NLF on wing upper and lower surface (70%) was transferred to Boeing Company for further detailed analysis (SUGAR TBW concept).
Mallik et al. [267] / 2015	7730	48000	305	0.85	23.1	6	MDO of TBW concepts considering the effects of flutter. Data for minimum-fuel objective and advanced aerodynamic technology levels over CTW aircraft with same technology.
Ma et al. [268] / 2022	3400	33000	186	0.78	18.3	23.1	Conceptual design of different SBW concepts with advanced airframe technologies and materials. A comparative study over twin-fuselage concepts is also discussed in this article. Data for medium-range mission, and performance benefits compared to A320neo aircraft.

Table 9: Summary of SBW and TBW concepts using high-fidelity tools.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Carrier et al. [269] / 2012	3000	39000	150	0.75	-	5.7	MDO of the Albatros project carried out by ONERA. The SBW concept increased the wing aspect ratio while decreasing sweep angle and airfoil thickness, resulting in laminar flow across a significant portion of the wing surface. High-fidelity aerodynamic and structural analyses can be found in [270].
Bradley et al. [99] / 2015	900	40800	154	0.72	18.1	56	SUGAR High (765-095) concept - a high aspect ratio SBW design with 2030s advanced technologies (primarily to wing weight, propulsion, and aerodynamics). Fuel efficiency relative to current CTW.
Bradley et al. [100] / 2015	900	42000	154	0.72	17.9	63.4	SUGAR Volt (765-096) concept - a similar layout to the SUGAR High that has been resized to accommodate modular battery packages and a hybrid gas turbine electric propulsion system. Fuel/energy efficiency relative to current CTW.
Droney et al. [101] / 2020	900	40000	154	0.74	19.4	57	Sugar High (765-095 Rev-J) - a transonic TBW variant. Higher-order tools were used to create this concept, which was then tested in a wind tunnel. Fuel-burn benefits compared to a CTW with technology levels representative of the 2008 single-aisle fleet.
Gagnon and Zingg [271] / 2014	550	34500	100	0.78	-	-	High-fidelity optimization of several unconventional concepts using an Euler-based approach. The SBW showed an inviscid drag reduction of roughly 40% compared to a conventional reference.
Moerland et al. [272] / 2017	1700	42093	154	0.72	19.1	32	SBW carried out by DLR applying collaborative design. The concept includes open rotors as novel propulsion technology and NLF.
Torrigiani et al. [273] / 2018	1890	36000	90	0.78	-	0.87	SBW from AGILE project. This aircraft included board system design and cost assessment, proving that when several systems are included in the design space, only a minimal improvement over the conventional reference can be achieved.
Secco and Martins [274] / 2019	-	30000	-	0.72	14.9	-	RANS-Based aerodynamic shape optimization of an SBW concept. Total drag reduction of about 14.7%.
Maldonado et al. [275] / 2020	-	40000	-	0.74	16.7	-	Computational analysis of a TBW concept using unstructured and structured grids. Experimental campaign findings were compared to computational aerodynamic data.
Chau and Zingg [129] / 2021	500	44670	104	0.78	16.4	7.6	Conceptual-level MDO and aerodynamic optimization of an SBW concept using a RANS-based approach. Performance benefits are given assuming 2020 technology levels.



(a) Baseline conventional aircraft.

(b) C-tip BWB aircraft.

(c) Box-wing aircraft.

(d) Strut-braced wing aircraft.

Figure 8: Regional transports, dimensions in meters (source from Gagnon and Zingg [277]).

lower transonic wave drag. This condition also allows for a smaller wing sweep, which can help to reduce wing weight while permitting natural laminar flow over the wing, which reduces viscous drag. However, some uncertainty remains regarding buffet margin for the strut's upper surface at a maximum operating Mach number. This problem could cause unacceptable vibration levels in the airframe, limiting the performance envelope. (ii) The TBW concept allows for higher aspect ratios than the SBW, providing a significant reduction in induced drag, but introduces additional challenges in shock elimination. However, given the large wingspan of both concepts, folding wingtips are mandatory in order to meet the gate constraints of the airports.

Regarding the structural and aeroelastic characteristics of these configurations, the best flutter performance for SBW occurred when the wing and strut had the same sweep angle, whereas the TBW provided the best flutter performance using a swept-forward strut, reducing both the natural frequencies and flutter speed [282]. Cost-benefit analyses are needed to determine the feasibility of using active flutter-suppression mechanisms, as current technologies may add weight, impacting on the gross take-off weight or the fuel-burn [283]. In conclusion, both the SBW and TBW concepts are promising innovative designs for next-generation airliners, with the highest TRL among other unconventional configurations [220].

4.4. Advanced Propulsion Concepts

Airframe-propulsion integration is considered one of the most important aspects in aircraft design, since the Specific Fuel Consumption has a direct impact on the DOC of a new aircraft. The most conventional way to reduce the Specific Fuel Consumption is increasing the bypass ratio, which improves the propulsive efficiency by increasing the mass flow rate. However, the integration of high bypass ratio engines using pylons results in a large wetted area and heavier structures, increasing fuel-burn [284]. In addition, current landing gear heights are unable to accommodate further increases to bypass ratio/engine diameters, as the weight increase

Figure 9: SUGAR Volt aircraft (source from [281]. Credits: NASA/The Boeing Company).

incurred by extending landing gear height to accommodate these larger engines is not a viable alternative from an economic point of view [285]. As a result, most novel propulsion concepts integrate the engines in alternative positions, providing drag and acoustic benefits [286]. For example, distributed propulsion, BLI propulsion, and electrified propulsion are projected to maximize vehicle benefits by coupling propulsion and wing aerodynamics. These advanced technologies have enabled engineers to design new types of aircraft that will serve new roles in the future.

There are appropriate reviews summarizing the most important developments in terms of aircraft propulsion technology. For example, Gohardani et al. [50, 51] reported complete literature revisions of design challenges of distributed propulsion technology and its potential application on next-generation commercial aircraft. Conventional and alternative configurations were extensively reviewed, highlighting the potential application of distributed propulsion using podded and BLI technologies on BWB and HWB configurations. Other literature reviews involving BLI modeling and its effects on aircraft design can be found in [55, 56, 57, 58].

More than 70 all-electric conceptual, experimental, and commercial aircraft along with progress in battery technology were reviewed by Gnadt et al. [61]. In this case, the performance of such aircraft was compared to advanced fuel-powered CTW aircraft at the same design range. Performance limitations of full-electric aircraft are presented by Hepperle [62], where a variety of propulsion systems were investigated with a focus on energy and battery storage systems. Recently, Brelje and Martins [64] reported an overview of electrical components and electric propulsion architectures. The authors reviewed existing commercial products, demonstrators, and conceptual design studies, in order to provide a list of potential benefits and disadvantages of electric propulsion for future high-fidelity multidisciplinary design of electric aircraft.

This section summarizes the unconventional concepts that have been designed with revolutionary propulsion technologies for commercial aviation. Some of them are already described in the previous sections due to their synergy with innovative airframes. Tables 10, 11, and 12 list other design studies by academia, government entities, and industry, arranged by the type of propulsion system, showing the product of Mach number and lift-to-drag ratio (ML/D) at cruise, as well as fuel/energy benefits over conventional propulsion systems. Each of the configurations involve multiple technologies with different payload and range capabilities. The results of the studies described in the three tables can be summarized as follows:

- The concepts described in Table 10 show how the benefits of boundary layer ingesting and distributed propulsion systems can minimize the fuel-burn by improving propulsive efficiency. However, such configurations are exposed to flow distortion arising from airframe separation, causing pressure losses, vibration, and noise. Therefore, the integration of distortion tolerant fan blades is mandatory, in order to operate at their maximum design performance. It is worth clarifying that the methods used to evaluate the benefit of boundary layer ingestion differ among the referenced studies. For example, the older studies were limited to 1D propulsion system modeling and simulation, whereas some of the most recent studies involve numerical simulations to account for complex flow interactions, such as fully coupled body force models. In this context, the prediction of the potential gains of BLI in aircraft design requires propulsor models that accurately estimate upstream interaction of the fan with the non-uniform inlet flow. Figure 10 shows a rendering of innovative propulsion technologies explored by different research institutions. The Double Bubble D8 concept (Fig. 10a) integrates potential technologies such as a lifting fuselage, BLI engines, a low-sweep wing that contributes to a lighter structure, and a lower cruise speed (Mach 0.72) than typical commercial aircraft (Mach 0.78). This concept provides a 30% fuel-burn benefit relative to a conventional aircraft with 2010 technology [288]. The NASA STARC-ABL concept (Fig. 10b) integrates turboelectric propulsion with an electrically driven BLI mounted on the fuselage tail cone, providing a 12% fuel-burn benefit over conventional aircraft with advanced aerodynamic technologies for entry into services in 2035 [292].
- Open rotors in the single-aisle category (shown in Table 11) have demonstrated high propulsive efficiency, approximately on the order of 86%, at 0.72 Mach, allowing for a 30% reduction in fuel-burn over conventional turbofan engines [47]. The high propulsive efficiency is a function of the difference between the jet velocity and the ambient velocity, i.e., open rotors have the capacity to accelerate a large mass flow rate, increasing the effective bypass ratio to more than 30:1 [48]. Despite

Table 10: Summary of Boundary Layer Ingestion concepts.

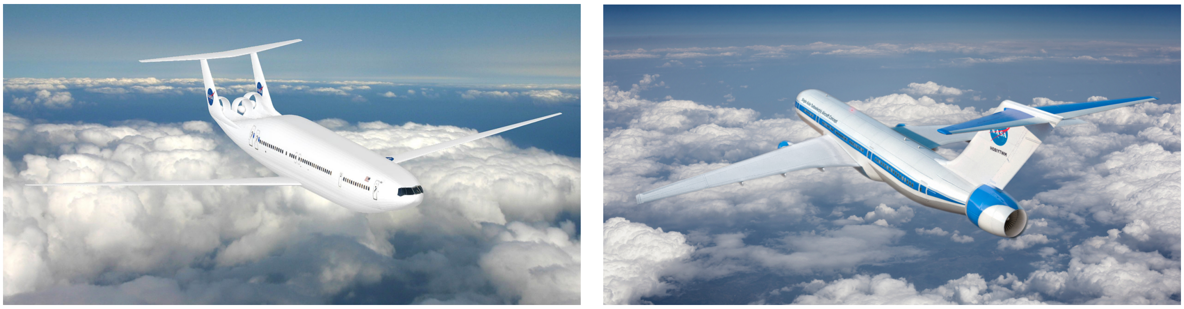
References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Drela [147] / 2011	3000	39000	180	0.72	16.8	33	Double Bubble with Aft-integrated BLI propulsion (D8). CFD simulations and wind tunnel experiments have been carried out on this concept [287, 288].
Singh et al. [289] / 2014	4800	41000	340	0.8	21.8	8.9	Conceptual design of propulsive fuselage concept from DisPURSAL project. Propulsion system was sized using parametric models for integrated aircraft.
Wiart et al. [290] / 2015	3000	37000	180	0.82	17.2	-	NOVA concept from ONERA including side-mounted BLI engines. RANS simulations coupled with an actuator disk evaluated the propulsion-airframe integration characteristics.
Bijewitz et al. [291] / 2016	4800	41000	340	0.8	24.7	9.4	MDO of propulsive fuselage concept from DisPURSAL project. The propulsion system was modelled using CFD and gas turbine performance estimates.
Welstead and Felder [292] / 2016	3500	38500	154	0.72	16.5	12	NASA's STARC-ABL aircraft. A turboelectric propulsion system with an electrically driven BLI mounted on the fuselage tail cone. Fuel-burn benefits relative to an advanced conventional reference. High-fidelity optimization studies can be found in [293, 294, 295, 296, 297].
Seitz et al. [298] / 2021	6500	41000	340	0.82	17.0	11.3	Proof of concept study of Centreline concept with propulsive fuselage by Bauhaus Luftfahrt. Fuel-burn benefits relative to an advanced conventional reference.
Samuelsson et al. [299] / 2021	3500	37000	180	0.8	19.6	7.8	Propulsive Fuselage with turbo-electric propulsion and advanced technologies (NLF on nacelles, variable camber and high aspect ratio wings).
Ahuja and Mavris [300] / 2021	3450	35000	180	0.78	-	-	This study focused on aero-propulsive coupling during the conceptual design of top-mounted and side-mounted BLI configurations.
Karpuk and Elham [117] / 2021	2000	35000	200	0.78	17.2	43.6	This aircraft combines the benefits of forward swept wing, active load alleviation and BLI technologies in a multi-fidelity approach. This concept reduces fuel-burn by 43.6% compared to a conventional aircraft with 2020 technology.
Secchi et al. [301] / 2021	1500	35000	84	0.75	10.7	7	Regional aircraft with a BLI electric engine at the fuselage tail cone. This study implemented parametric variations of the thrust split ratio and electric fan pressure ratio.

Table 11: Summary of open rotor concepts and new turboprop aircraft.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Guynn et al. [302] / 2009	3060	35000	162	0.72	-	24	This paper describes assessments of an open rotor aircraft. The open rotor aircraft is predicted to have 24% lower fuel-burn than a 1990s reference baseline aircraft.
Larsson et al. [303] / 2011	3000	35000	150	0.73	-	15	Multidisciplinary conceptual design of an open rotor configuration using low-fidelity tools. Fuel-burn benefits relative to a 2020 technology conventional aircraft.
Raymer et al. [121] / 2011	2774	30000	180	0.8	20	60	Advanced transport aircraft concept including tandem open rotors and NLF wings. Fuel-burn benefits relative to a 2010 technology conventional aircraft.
Guynn et al. [304] / 2011	3250	35000	150	0.72	15.4	30	Medium-fidelity conceptual design of an open rotor concept. Fuel consumption reduction relative to 1990s technology.
Perullo et al. [305] / 2013	-	35000	-	0.8	-	29	Advanced open rotor performance modeling for multidisciplinary optimization evaluations. Fuel consumption reduction relative to a modern baseline.
Gern [306] / 2013	6500	35000	244	0.8	-	-	Conceptual design of an HWB including open rotors. This concept was subjected to both low- and high-fidelity structural investigations.
Bradley et al. [99] / 2015	900	41500	154	0.70	18.1	56	SUGAR High (765-095-RevD-UDF) concept - an Unducted Fan architecture for the TBW airframe. The performance is shown relative to a CTW with 2008 technology levels.
Dorsey and Uranga [307] / 2020	4000	37000	200	0.78	13.75	-	Design exploration of open rotor concepts. Data for a wing-mounted open rotor using medium-fidelity tools; other categories and engine location were evaluated.
Nicolosi et al. [119] / 2021	1600	37000	130	0.68	12.7	17.2	Low-fidelity MDO of large turboprop aircraft. Data for a three lifting surface concept with rear-mounted engines.

Table 12: Summary of electric fixed-wing aircraft concepts.

References / Year	Range [nm]	Cruise altitude [ft]	No. passengers	Mach number [-]	ML/D [-]	Fuel-burn reduction [%]	Remarks
Hornung et al. [308] / 2013	900	34000	190	0.75	15.5	-	C-wing concept with super-conducting electric engines.
Strack et al. [309] / 2017	800	23000	70	0.41	9.6	4	Conceptual design study of hybrid electric turboprop aircraft configurations. Data for a parallel hybrid architecture with a high aspect ratio wing, electrically driven propellers at the wingtip and reduced vertical tailplane. Fuel-burn benefits relative to an advanced EIS 2035 turboprop without hybrid electric propulsion.
Voskuijl et al. [310] / 2018	825	25000	70	-	-	28	Design of hybrid electric regional turboprop aircraft. All the analyses are based on relatively low fidelity methods. Fuel-burn benefits relative to a fuel-powered conventional aircraft. This comes at the cost of a larger and heavier aircraft.
Schmollgruber et al. [311] / 2019	1200	33000	150	0.78	14.9	8.5	DRAGON concept from ONERA using multidisciplinary low-fidelity aerodynamics. The aircraft includes a hybrid electric distributed propulsion system.
Schiltgen et al. [312] / 2019	900	35000	150	0.78	16.9	11	ECO-150-300 concept. A distributed electric propulsion concept subjected to an extensive CFD study for external and internal aerodynamic performance.
Hoogreef et al. [313] / 2019	800	33000	150	0.78	-	10	Conceptual design of 35 hybrid-electric aircraft. Data for a boosted turbofan parallel hybrid concept. Comparison over conventional turbofan aircraft.
Vries et al. [314] / 2019	825	18000	72	0.41	7.5	-	This study presented a low-order MDO environment that can capture the unique features of serial/parallel hybrid-electric aircraft. Data for partial-turboelectric powertrain with distributed propulsion. This concept consumes 3% more energy than a conventional configuration.
Sgueglia et al. [315] / 2020	1500	40000	150	0.78	14.4	-	High-fidelity MDO of a hybrid-aircraft concept with distributed electric ducted fans.
Vries and Vos. [316] / 2022	1500	36000	75	0.6	-	5	This study presented an aerodynamic evaluation of an over-the-wing distributed-propulsion for hybrid-electric transport aircraft. Comparison over conventional twin-turboprop reference for the 2035 timeframe.
Jansen et al. [317] / 2022	750	37000	180	0.78	-	26.8	The SUSAN Electrofan Variant 3. A ducted turbofan propulsor concept which includes a gearbox to improve propulsive efficiency. Fuel-burn benefits compared to a CTW with technology levels representative of the 2005 single-aisle fleet. More details of several disciplines can be found in [318, 319].



(a) The Double Bubble D8 (source from [320]. Credits: NASA/MIT/Aurora Flight Sciences).

(b) NASA's STARC-ABL concept (source from [281]. Credits: ASAB Projects).

Figure 10: Revolutionary BLI concepts.

significant progress on these concepts, important challenges require further research efforts in terms of propulsion airframe integration, noise and weight penalties, and certification issues.

- Table 12 summarises aircraft concepts incorporating electric or hybrid-electric engines with various types of integration. The implications of using electric or hybrid power architectures, i.e., concepts that combine different power sources such as gas turbines, advanced batteries, or liquid hydrogen fuels, dictate innovative approaches and can significantly reduce emissions from commercial aircraft. However, the main disadvantage is their restricted range, which is determined by the amount of batteries they can carry. The battery use itself brings challenges such as the weight on board, which reduces payload capabilities, and its specific energy, which reduces the operating capabilities [321]. For that reason, full-electric propulsion is currently being implemented in general aviation, urban air taxis, and commuter aircraft, which require less demanding requirements [322]. In contrast, hybrid-electric systems and turbo-electric systems are well-suited for application on distributed propulsion architectures for civil aviation. Nevertheless, in terms of aircraft performance, research into realistic aircraft systems integration and implementation is currently at a low TRL. Simplified models to forecast the performance of those concepts are widely available, but a detailed and accurate portrayal of the interaction between the propulsive system and the airframe is essential, as the two parts work in synergy. Indeed, the benefits of distributed propulsion concepts have been shown to be affected by structures, vibrations, and acoustics problems, given the unsteady nature of the flow interactions. Therefore, the implementation of high-fidelity aerodynamic shape optimization can provide a better understanding of such time-dependent problems [323]. Finally, there are challenges for airport infrastructure and ground operations arising from aircraft concepts using alternative sources of energy [324, 325].

To conclude this section, the latest efforts to develop hydrogen-powered commercial aircraft are mentioned. According to Khandelwal et al. [35], hydrogen stores three and a half times more energy than kerosene per unit weight, which undoubtedly represents an advantage compared to traditional aviation fuels. However, it presents an energy density three times lower than that of kerosene per unit volume. Therefore, the main issue is the volume needed on board to transport the same amount of energy as conventional fuels. As a result, very large tanks are required, particularly because the hydrogen must be stored as a cryogenic fluid at $-423^{\circ}F$ [36]. That is why hydrogen-powered aircraft consider cryogenic hydrogen tanks in the fuselage, rather than in the wings. This influences the shape of the aircraft, and therefore the aerodynamics [326]. Brelje and Martins [327] explored the aerostructural wing optimization for a hydrogen fuel cell aircraft. The findings indicate that storing compressed hydrogen in the wing root of a single-aisle transport aircraft could be a viable option at conceptual design level. However, due to the weight and volumetric capacity of compressed hydrogen storage tanks, it is unlikely to be used on transcontinental routes.

Rompokos et al. [328], and Druot et al. [329] have presented several unconventional configurations using external and internal hydrogen tanks. In either case, there are trade-offs between external aerodynamics and the issue of integrating very big tanks within the airframe, which can affect payload volume and fuel capacity. The BWB is thought to be a feasible solution for this idea, although other potential configurations are the Twin Tail-Boom and Tail-Tank concepts.

Three hydrogen-powered concepts were presented by Airbus in the context of French public support for the aviation sector in the COVID-19 crisis: a BWB aircraft for up to 200 passengers, range of 2000 nm, and hybrid hydrogen turbofan engines; a regional aircraft for up to 100 passengers, range of 1000 nm, and hybrid hydrogen turboprop engines; a single-aisle aircraft for 120-200 passengers, range of 2000 nm, and hybrid hydrogen turbofan engines. All are capable of a Mach 0.78 cruise speed [330, 331].

Given the potential of new propulsion technologies for modern and unconventional configurations to reduce emissions, it is necessary to evaluate economic variables such as DOC in order to quantify the potential economic benefit for airlines and to quantify the cost and risk associated with development of such technologies.

4.5. Other Configurations

This section includes other unconventional configurations that have been investigated recently. The following configurations involve an original layout with reduced fuel-burn when compared to their CTW counterparts. Since there are major difference among these concepts, a precise classification was not made.

- Throughout aviation history, forward-swept wing concepts have been tested to improve aircraft performance in transonic and supersonic flight. The implementation in military aviation demonstrated a reduction in compressibility effects at transonic speeds and greater lift at low speeds [332]. However, earlier studies evidenced several aeroelastic problems such as divergence, flutter, buffeting, among others [333]. Composite materials and new additive manufacturing techniques can mitigate those problems, enabling also lightweight structures, a substantial increase in strength ratio, and reduction in maintenance cost [28, 33].

  For this reason, there is recent progress on forward-swept wing concepts for commercial aviation due to the synergy between active load control and natural laminar flow, which can yield to significant gains in terms of fuel and cost [334]. Iwanizki et al. [335] presents an overview of several forward-swept wing concepts investigated in the European Clean Sky 2 and ONERA-DLR projects. This paper showed that forward-swept wing concepts enable NLF at high Reynolds numbers, which reduce friction drag by delaying the onset of turbulent flow. The combination of forward-swept wing, NLF, and composite materials can offer fuel savings by about 18% compared to an improved conventional configuration with a backward-swept composite wing.

  Two configurations stand out within this group: the LamAiR concept [336, 337] designed with a forward-swept NLF wing, smart droop nose leading edge high-lift device, and carbon fiber reinforced polymer wing; and its successor the TuLam concept [338] designed with similar characteristics of the LamAir concept, but adding HLFC systems. Both studies followed a high-fidelity MDO process, obtaining an overall aerodynamic performance at cruise (ML/D) equal to 14.9 and 16 respectively, at design cruise Mach of 0.78.

- The twin-fuselage concept has also been proposed as an alternative commercial airliner. Some early designs demonstrated a substantial increase in aspect ratio while reducing the bending moment in the wing root sections. As a result, this configuration provides an operational empty weight reduction without compromising payload capacity [339]. This advantage has enabled engineers to include additional technologies such as HLFC and active load alleviation, offering additional fuel-burn benefits [340]. This particular concept was designed using a multi-fidelity approach involving low-fidelity aerodynamics and a semi-analytical equation for wing mass calculation. The results show that twin-fuselage concepts combined with advanced aerodynamic and structural technologies provide an aerodynamic performance (ML/D) equal to 18.33 at cruise Mach of 0.78, which can reduce fuel-burn by roughly 30% over the current conventional configurations. However, high-fidelity studies are required to evaluate the benefits of this concept.

  Design challenges of twin-fuselage concepts include a significantly higher wetted area than single-fuselage concepts of equivalent capacity, so friction drag can be higher than conventional aircraft. In addition, twin-fuselage aircraft are prone to produce interference drag penalties. Other issues include roll stability requiring larger rolling moments, so ailerons must be larger or placed farther away from the centerline, which increases the weight of system and operational items. Operational challenges involve current airport infrastructure requiring wider runways due to the arrangement of the landing gears. In addition, the high aspect ratio wings are not able to operate on current airport gate-box limits. This problem can be solved in a similar way to truss-braced wing concepts, which require folding wing tips; however this adds wing weight [341].

- The Flying V concept (Fig 11) presents an innovative tailless airframe, whose wings act as passenger cabin, fuel tanks, and cargo haul. Such an arrangement provides a lower aerodynamic drag than CTW aircraft, since the wetted area is reduced, thus reducing the friction drag, and the effective wingspan is increased, lowering lift-induced drag. Fuel-burn benefits reach 20% over a comparable CTW aircraft, providing overall aerodynamic performance at cruise (ML/D) equal to 20.14 at Mach 0.85. This concept has also demonstrated a reduction in empty weight as well as lower noise inside the cabin [342]. High-fidelity aerodynamic studies, including CFD and wind-tunnel experiments, have determined the ideal engine location as well as the arrangement of control surfaces on this concept [343, 344].

  Despite the fact that conceptual studies have shown cost-effective fuel-burn advantages over the CTW arrangement, this concept presents a number of potential issues that need to be investigated further, such as the overhaul of cabin interiors to improve the overall flying experience, and the fact that fuel tanks are located on the same level as the passengers cabin, creating potential risk in case of incidents. The flight envelope also needs to be improved in order to minimise the rate at which the aircraft manoeuvres while maintaining flying safety. The high angle of attack needed during take off and landing could also put passengers in an uncomfortable position, especially if the seats are at an angle to the direction of flight. Staggered seats might be a solution for a V-shaped aircraft, but evacuation plans and more detailed designs are needed [345]. Since the Flying V has no tail, it requires a big landing gear to meet takeoff and rotation requirements; this creates integration issues because the landing gear has to fit inside the fuselage.

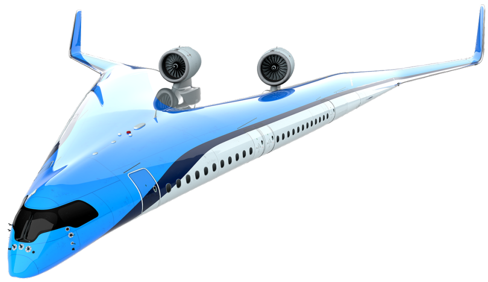


Figure 11: Flying V concept (source from [346]. Credits: TUDelft).

4.6. Other Technologies

Up to this point, the literature reviewed for this paper focused on describing the main design characteristics, design methodologies, and potential fuel burn reduction offered by several unconventional configurations. This section discusses other potential technologies that can be used in conjunction with unconventional configurations in order to achieve improvements in performance and reductions in fuel consumption. According to Bushnell [347], there are available and emerging technologies that reduce aircraft operating costs and emissions through simultaneous optimization of ML/D, acoustics, and weight. For example, natural laminar flow uses a careful geometric design to delay laminar-turbulent transition passively, whereas hybrid laminar flow control techniques delay transition with the help of suction through slots or small holes. The use of natural laminar flow is more suitable for smaller aircraft such as regional or commuter categories, due to their relatively low Reynolds numbers and potentially lower Mach numbers enabling reduced wing sweep angles. SBW and TBW concepts can also take advantage of such technology, since the use of external trusses reduces the wing weight, allowing the wings to be thinner than those of conventional aircraft, reducing wave drag and enabling reduced sweep and thus crossflow instabilities. On the other hand, aircraft with higher Reynolds numbers and sweep angles, such as twin-aisle aircraft, require active laminar flow control. The use of these systems often imposes operational penalties because of the additional weight or system complexity that, along with significant operational challenges, have restricted their use in transport aircraft [18]. In contrast to SBW and TBW aircraft, the high sweep angles typical of BWBs are better suited to hybrid laminar flow control [25].

Other viscous drag reduction technologies include: riblets, which have been studied to evaluate their performance on several TBW configurations [262]; plasma actuators, which have demonstrated an increase in the lift-to-drag ratio when applied on swept wings, as well as noise reduction benefits when applied in high-lift devices [348]; and morphing wings [148], including variable camber concepts using existing control surfaces [349]. In case of induced drag, the use of wing-tip devices such as blended winglets, Whitcomb winglets and sharp-ranked winglets, provide an effective aspect ratio improvement without great span increase [22]. From there, several wing-tip extensions have been proposed, presenting interesting aerodynamic and control implications, such as the C-wing concept, tip sails, spiroid tips and even morphing winglets [350, 351, 352, 353].

In terms of weight reduction approaches, advanced composites have been used to reduce the aircraft structural weight. Their lightweight and substantial strength ratio enhance aircraft performance and reduce maintenance costs. Other benefits include reduction of parts, reduction of scraps, improvement of fatigue life and improvement of corrosion resistance [31]. According to Soutis [30], an empty weight reduction can be achieved by using developments in the following areas: advanced metallic technologies, advanced composite technologies, and optimized local design. In case of metallic technologies, new alloys with specific properties are being developed. For example, a lower density has been obtained by aluminum-lithium alloys and higher permissible stress alloys. In addition, the use of fiber/metal laminates and metal laminates structures often saves some mass. For composite materials technologies, different lay-ups obtained through optimization techniques may result in high-strength fibers with improved matrix properties [32]. New composite sandwich panels with truss-like cores have the potential to take the place of metallic panels [33]. Finally, potential improvements through optimized local design can be obtained, such as the use deployable chutes for refused takeoff instead of heavy brakes, and new additive manufacturing processes that allow to obtain more precise geometries, as well as greater emphasis on the material properties of the components [347].

5. Discussion

As noted in the previous section, several unconventional aircraft have been investigated towards the next-generation airliner. All those studies showed improvements in fuel-burn compared to equivalent conventional aircraft. However, in order to achieve these benefits, some configurations must cruise at altitudes higher than is currently typical. This could introduce air traffic management challenges as such aircraft are introduced into the fleet, but more importantly in our current context, a high cruise altitude has implications for block fuel burn, especially for short-range missions, and for climate change impact.

Following the same path as Green [16, 17], we derive an expression for the dynamic pressure that minimizes the drag for a given aircraft (Eq. 1):

$$q_{\infty}^{2} = \frac{(W/S)^{2}}{C_{D0}\pi \mathcal{R} e} \tag{1}$$

where q_{∞} is the freestream dynamic pressure, given by ($q_{\infty} = \rho_{\infty} U_{\infty}^{2}/2$), ρ_{∞} is the fluid density, U_{∞} is the freestream speed, W/S is the wing loading, C_{D0} is the zero-lift drag coefficient, $\mathcal{R}$ is the aspect ratio, and e is the span efficiency factor. For a fixed U_{∞}, a lower optimal q_{∞} requires a lower density and thus a higher altitude.

For this reason, in order to profit from their unique design features and reduce fuel consumption, the majority of the unconventional configurations detailed in Section 4 have optimal cruise altitudes higher than typical altitudes for conventional aircraft. For example, BWBs and HWBs are characterized by their large reference area, i.e., low wing loading (W/S), and hence the optimal altitude is higher than for an aircraft with a higher wing loading. Similarly, SBW and TWB aircraft, whose fuel-burn benefits come from their high aspect ratios ($\mathcal{R}$), have a higher optimal altitude than conventional aircraft with lower aspect ratios. Finally, BW aircraft are characterized by high e values, which also decreases the optimal dynamic pressure, and thus require a higher cruise altitude than conventional aircraft.

Increasing cruise altitude has some significant drawbacks, including increased fuel burn during the climb segment of the flight, which is particularly significant for short-range missions. In addition, the climate change impact from NO_x emissions is sensitive to altitude, and it is important that this be taken into account when considering the overall benefits of a novel configuration. This effect could be mitigated if NO_x emissions can be reduced through low NO_x combustors or alternative fuels.

For all-electric or hybrid-electric aircraft, the optimum flight speed and altitude are restricted by the ratio of power generated by an electric engine in a hybrid aircraft to the total power consumed by the aircraft (i.e., degree of hybridization), as well as the risk of electrical arcing at high altitude. More details about the optimal flight conditions for a hybrid-electric aircraft were described by Pornet and Isikveren [63].

It is not yet clear what energy source or sources will facilitate aviation's path toward zero emissions that contribute to climate change. Biofuels, electrification, and hydrogen are all being pursued. Such energy sources are likely to be significantly more expensive than kerosene for the foreseeable future, and availability will also be an issue. Consequently, the potential improvements in energy efficiency associated with the unconventional aircraft configurations reviewed here can play an important role in facilitating the introduction of alternative energy sources by mitigating their adverse economic impact.

6. Conclusions

Next-generation civil transport aircraft must have greatly reduced environmental impact while remaining economically viable, meeting the many constraints associated with the air transportation system, and maintaining the necessary level of safety. While the conventional configuration has served well over many decades, it is an open question whether it will remain the optimal solution in the future. Considerable research has been conducted to develop and investigate unconventional aircraft configurations which have the potential to displace the conventional configuration as a result of their potential improvements in environmental and economic performance. A review of this research has been presented here with the objective of providing the reader with a summary of the benefits, challenges, and trade-offs associated with the various concepts currently under consideration.

Given the paucity of design experience with unconventional aircraft configurations, virtually all of the studies described rely on some sort of physics-based design tools, ranging from simple and fast conceptual design methodologies through multidisciplinary optimization frameworks where the aerodynamics discipline is based on the numerical solution of the Reynolds-averaged Navier-Stokes equations. The purpose of the studies reviewed is generally twofold. First the authors seek to develop solutions to the design challenges faced by the unconventional configuration under study and to develop a preliminary model of such an aircraft. This model is then used to provide a performance estimate of the novel configuration relative to a conventional tube-and-wing aircraft designed and evaluated consistently for the same mission. The development of accurate estimates of such performance benefits is crucial to enabling industry to make informed decisions on whether to commercialize a given configuration. The credibility of performance estimates for unconventional aircraft configurations depends on both the number of disciplines included in the design as well as the level of fidelity of the analysis. Both of these have steadily evolved over the years such that the relative performance of several unconventional configurations is now moderately well understood, although there remains work to be done to determine which configuration should be selected for a given aircraft class.

The studies discussed make various assumptions with respect to technology levels, which can make direct comparisons difficult. Some studies assume next-generation technologies in all aspects, such as engines. It is then critical to compare with a tube-and-wing that is also equipped with next-generation technologies. Other studies assume current technologies and can therefore be compared with today's most efficient aircraft in order to assess the benefit of the configuration alone. A disadvantage of this latter approach is that the aircraft developed will not be representative of the aircraft that could eventually be built, which will be equipped with next-generation engines, for example. A major advantage, however, is that this approach reduces the guesswork associated with new technologies in terms of their viability and effectiveness, hence providing a credible estimate of the impact of the configuration on its own, although this may not be possible when several new technologies are tightly integrated. In any case, it is important for the reader to be careful to have a clear understanding on the technology assumptions made in making an assessment of a particular concept.

In evaluating unconventional aircraft configurations, benefits and risks must be weighed against one another. For example, the TBW/SBW and BW have reduced risk relative to an HWB because they can use existing fuselage technology. Another important consideration is the trade-off between competing priorities, such as fuel efficiency, climate change impact, and noise. A clear understanding of how these are to be prioritized will be needed in order to choose the most promising configuration. Finally, the optimal configuration may be different for different aircraft classes, and the benefits of unconventional configurations depend on the aircraft class.

Aviation must reduce its environmental impact as quickly as possible. Adding advanced technologies to the conventional configuration can be accomplished in a fairly short time frame and should be aggressively pursued. Based on the studies presented, it appears that a strut-braced-wing configuration could be brought to market in the medium term and could provide significant benefits in the single-aisle and regional classes. The hybrid wing-body, on the other hand, may offer a better solution in the long term, especially for large long-range aircraft. Given the urgency of the environmental challenge, unconventional aircraft configurations with both medium and long term potential should be pursued, with academia and government continuing to pave the way until the cost and risk can be reduced to the point where one or more unconventional configurations can be commercialized.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors' intent in generating this review was to summarize the available literature from a compilation of different design proposals of unconventional configurations. This publication is dedicated to the many scientists and engineers who have devoted a portion of their careers toward developing new technologies which will someday lead to the next-generation of aircraft.

Special thanks to Prof. Dr. Hernán Darío Cerón-Muñoz, Prof. Dr. Alvaro Martins Abdalla, and Prof. Dr. James Rojas Waterhouse for their important contributions during the evaluation of the work presented hereby. The authors would further like to thank Ph.D. Paola Andrea Ayala-Burbano for the entire support during the papers acquisition and data organization.

The authors gratefully acknowledge the members of the Computational Aerodynamics Group at the University of Toronto Institute for Aerospace Studies for their insights and important discussions about unconventional aircraft. The authors also acknowledge the input and support provided by the members of the Experimental Aerodynamics Laboratory (LAE) at the Department of Aeronautical Engineering of the University of São Paulo (EESC-USP).

The authors disclosed receipt the following financial support for the research, authorship, and/or publication of this article: this work was financed by the National Council for Scientific and Technological Development - CNPq (grants 141950/2017-0 and 203402/2019-7).

Appendix A. Literature Review Protocol

First of all, we defined a set of "key-words", "search strings" and search limitations in order to classify each paper regarding the subjects under evaluation. Search strings were composed by combining key-words. Search limitations refer to the selection and rejection criteria. Once determined the aforementioned parameters, we selected the search sources for the review methodology, in this case, the ISI Web of Science database and Google scholar. The ISI Web of Science database includes peer reviewed papers from other databases (such as Scopus, AIAA and Wiley) that were published in indexed journals with a calculated impact factor in the JCR (Journal Citation Report). Google scholar aided to include "grey literature" such as reports arising from conferences and symposiums, as well as master's dissertations, Ph.D. theses, and technical reports. No limitation on year of publication was imposed on the database searches. The search criteria is provided in Fig. 12. In sum, the complete literature sample consisted of 203 journal articles, 88 conference papers, 36 technical reports, and 26 additional references (including thesis, books and websites).

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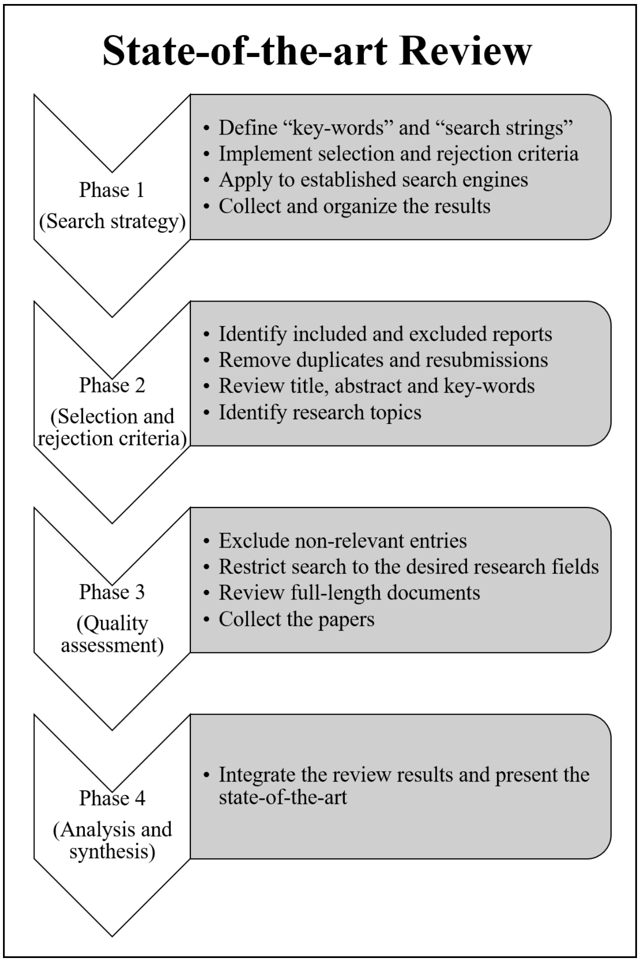

Figure 12: Synthesis of the state-of-the-art review.

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