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Boundary Layer Ingestion Propulsion: a Review on Numerical Modelling

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Abstract

The present paper focuses on the numerical modelling approaches adopted in Boundary Layer Ingestion (BLI) studies. Three driving aircraft concepts have been identified, namely Propulsive Fuselage Concept, Rear Engines Concept and Distributed Fans Concept. The affiliation to relevant research projects has been considered. Specifically, European projects DisPURSAL and CENTRELINE, NASA projects STARC-ABL, D8, and N3-X, as well as ONERA projects NOVA and DRAGON have been examined, together with other significant works. The methodologies adopted by the reviewed analyses have been investigated and summarized for each concept, in order to assess the main trends of BLI modelling strategies.

Keywords: BLI, Propulsive Fuselage, Rear Engines, Distributed Fans, modelling, aircraft, propulsion

Nomenclature

D $[m]$	Diameter
$\dot{m}$ $[kg/s]$	Mass flow
M $[-]$	Mach number
n $[rpm]$	Rotation speed
P $[kW]$	Power
Greek	
η $[-]$	Isentropic efficiency
η_{pol} $[-]$	Polytropic efficiency
Acronyms	
2035R	2035 Reference
AD	Actuator Disk
BC	Boundary Conditions
BEM	Blade Element Momentum
BF	Body-Force
BL	Boundary Layer
BLI	Boundary Layer Ingestion
BPR	By-Pass Ratio
DFC	Distributed Fans Concept
HWB	Hybrid Wing Body
ML	Mean-Line
MTOW	Maximum Take-Off Weight
OEW	Operating Empty Weight
PC	Parallel Compressor
PFC	Propulsive Fuselage Concept
PR	Pressure Ratio
PRR	Pressure Recovery Ratio
PSC	Power Saving Coefficient
REC	Rear Engines Concept
SoAR	State-of-Art Reference
T&W	Tube and Wing
TeDP	Turbo-electric Distributed Propulsion
TF	Through-Flow
TSFC	Thrust-Specific Fuel Consumption
UHBR	Ultra-High By-pass Ratio
VL	Vortex-Lattice

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1. Introduction

1.1. Benefits and challenges

The current trend in civil aircraft industry is characterized by a growing demand and increasingly strict environmental regulations. In fact, the higher awareness about the impact of air transportation emissions is driving a low-carbon technology transition, towards more sustainable propulsion strategies [1–5]. Focusing on the challenges set by NASA N+3 and EU FlightPath 2050 visions, reported in Table 1, novel configurations are being investigated. The common goal is to increase the overall aircraft efficiency, minimize fuel burn, reduce emissions and enhance the acoustic performance of the system.

The unquestionable point is that a high level of engine-fuselage integration is expected, in order to meet the above mentioned goals. In fact, the combination of high-lift wings, wide airfoil-shaped body and embedded engines is believed to maximize the aircraft aerodynamic efficiency [6]. In this framework, the transition to a distributed propulsion approach appears as one of the most promising solutions and, in particular, Boundary Layer Ingestion (BLI) engines play a key role.

The BLI potential stands in the wake filling approach, sketched in Figure 1. The standard podded engines need to impress an over-velocity to the exhaust air flow, compared to the undisturbed velocity, to produce thrust. On the other hand, BLI engines feature an embedded configuration, so that part of the low-momentum boundary layer flow around the fuselage is ingested by the device. Therefore, the aircraft wake is re-energized, being filled by the propulsor exit flow, and the momentum deficit is partially recovered. Consequently, the exit velocity needed to produce the same thrust is reduced, giving a benefit in terms of reduced jet over-velocities and wake mixing losses, hence increasing propulsive efficiency.

The aerodynamic benefits coming from wake filling have long been studied. Nevertheless, the definition of a thrust-drag bookkeeping scheme which accounts all the forces on the integrated aero-propulsive system consistently is a major challenge in BLI modelling. Smith [8] proposed an Actuator Disk (AD) method to evaluate the amount of propulsive power saving which can be achieved thanks to the ingestion of body wake, by assuming a given boundary layer profile. He introduced the Power Saving Coefficient (PSC) metric, defined by Equation 1, where P_{BLI} and P define respectively the power needed to propel the aircraft with and without BLI. Positive values were obtained for BLI engines and, in particular, higher PSC were given by small propulsors, characterized by high thrust-loading coefficients.

	NASA N+3 2025–2035	NASA N+3 beyond 2035	EU FlightPath 2050
Fuel burn	-50–60%	-60–80%	-
CO_2	Neutrality	-50%	-75%
NOx	-80%	>-80%	-90%
Noise	-32–42 dB	-42–52 dB	-65%

Table 1: NASA N+3 and EU FlightPath 2050 goals on future aircraft development, improvements relative to year 2000 [3, 5].

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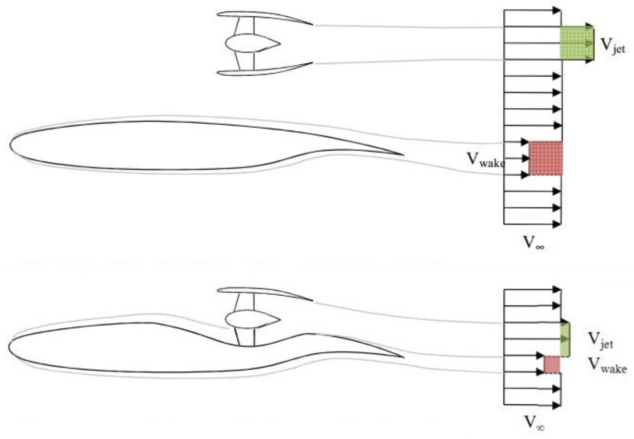

Figure 1: Traditional podded engine (top) and embedded BLI engine exploiting wake filling principle (bottom) [7].

$$PSC = \frac{P - P_{BLI}}{P} \quad (1)$$

Drela [9] developed a more general power balance modelling approach based on a control volume analysis, setting a fundamental strategy for BLI performance assessment. By splitting the wake losses into several contributions, without the need of computing drag and thrust of such integrated systems, the results consistently confirm the benefit of wake filling. Further power balance applications were proposed. Lv *et al.* [10] observed that the power reduction at equal thrust and flight conditions was coming from the lower downstream wake energy. Hall *et al.* [11] evaluated the BLI benefit for the D8 aircraft. They separated the reduced jet loss, due to low-momentum boundary layer ingestion, from the reduced airframe dissipation, linked to the smaller wetted areas and the re-energized wake, in order to weight the two contributions. The results of the control volume and 1D analyses indicated a mechanical power reduction, attributed as 60% to reduced jet mixing and 40% to lower airframe losses.

A further generalization of the power balance method came with the work of Arntz and Merlen [12], who developed the exergy-based approach, aiming to improve the far-field drag predictions of ONERA ffd72 code. Nevertheless, the need of separating thrust and drag components kept encouraging theoretical developments. Recently, Lord et al. [13] proposed to split the BLI benefit into exhaust jet and airframe wake dissipation reduction. Their method identifies an equivalent far-field state characterized by freestream static pressure. The advantage of such accounting procedure stands in the distinction between propulsion system efficiency and airframe drag.

Enhanced benefits arise from the combination between BLI principles and Turbo-electric Distributed Propulsion (TeDP). As reviewed by Kim [14], TeDP features a number of electric fans, remotely driven by a high-efficiency power plant. This arrangement leads to an improved configurational flexibility, as propulsion and power generation are decoupled, and electric motors performance scale almost linearly with size. Moreover, the transition to low-carbon technology is promoted. The

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goal is to assess whether the efficiency gain overcomes the weight penalties rising from the electric devices. In Figure 2 the schemes of partially and full TeDP propulsion system are given.

Before discussing the specific aircraft configurations, general pros and cons of BLI propulsion are hereby outlined:

- ⊕ The process of wake filling reduces the flow dissipation in the aircraft wake [8–10]. Moreover, a portion of aircraft wake ingested by the propulsion system is eliminated [13]. Hence, reductions in propulsive power demand, fuel burn and emissions are expected;
- ⊕ A close engine-fuselage integration reduces the total wetted area, yielding to a decrease in nacelle and pylon drag [11]. Furthermore, airframe structural relief is promoted [6];
- ⊕ The separation between power and thrust generation devices opens to high achievable by-pass ratios [15];
- ⊕ Improved noise shielding is expected for most of the configurations [16];
- ⊕ The adoption of TeDP allows a greater design freedom, and encourages the transition to low-carbon technology [14]. Furthermore, ehnanced wake filling and reduced intake losses can be achieved [17]. Moreover, improved flexibility in trhust split setting, reduction of noise, vibrations and thermal shielding requirements are expected [17];
- ⊖ The BLI engine operates under inherently non-uniform inlet flow conditions. For a conventionally designed fan, an efficiency loss is expected, together with a reduced surge margin [18, 19];
- ⊖ Propulsive efficiency is further reduced by a lower total inlet pressure recovery [11];
- ⊖ Structural fatigue issues can rise from unconventional engine installations [15, 16];
- ⊖ The introduction of TeDP cause an increase in aircraft weight [20]. Moreover, the potential risk linked to high-power electrical components on board has to be managed [16].

1.2. Structure of the review

In order to organize this literature review, three guiding aircraft families have been identified, namely Propulsive Fuselage Concept, Rear Engines Concept and Distributed Fans Concept. Moreover, since the current report focuses on numerical modelling, an overview on the simulation approaches is proposed. Methodologies have been investigated and summarized following BLI benefit drivers criteria, based on the definition of the baseline non-BLI aircraft, the thrust-drag bookkeeping scheme adopted and the control volume of the study.

For each family, the affiliation to relevant research projects has been considered, as discussed in Section 2, Section 3 and Section 4. Specifically, European projects DisPURSAL and CENTRELINE, NASA projects STARC-ABL, D8, and N3-X, as well as ONERA projects NOVA and DRAGON have been reviewed, together with other significant works. In the end, conclusions and final remarks are drawn in Section 5, in order to assess the main trends of BLI modelling strategies.

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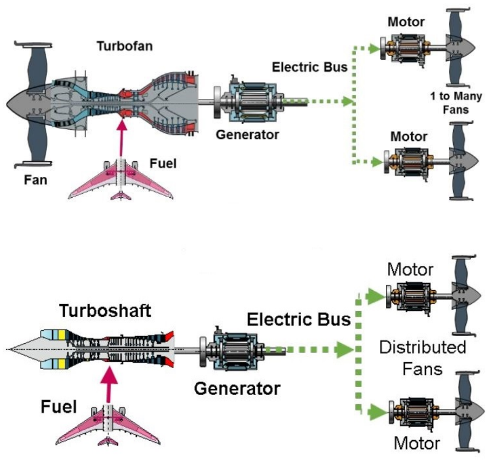

Figure 2: Partially (top) and full (bottom) turbo-electric propulsion schemes [21].

1.3. *Aircraft layouts*

Wake ingestion, already exploited in marine propulsion, was identified as a promising solution also for aeronautical applications. Recently, several aircraft concepts featuring BLI engines have been proposed, both by academia and industry [22]. The design space of such configurations is still under exploration, since many degrees of freedom are present. Moreover, a deeply interdisciplinary design is needed. In fact, the engine-fuselage integration inherent to the BLI philosophy requires a coupled analysis of propulsion system performance and vehicle aerodynamics. Last but not least, the redefinition of power control strategies and safety considerations is part of the framework. This study focuses on the most promising solutions for medium-to-long range transport applications which involve BLI engines.

Hybrid Wing Body (HWB) fuselage configurations featuring full TeDP are realizable considering a long-term goal (2050) [21]. In fact, technological barriers are currently present, since a deep architectural rethinking is required. Tube and Wing (T&W) airframe powered by partial TeDP, based on moderate and feasible technology advances, can be identified as a closer mid-term goal (2035).

The aircraft layouts analysed in the present work have been grouped into three families: Propulsive Fuselage Concept (PFC), Rear Engines Concept (REC) and Distributed Fans Concept (DFC). Steiner *et al.* [23] estimated the maximum ideal PSC for these concepts, through a comprehensive classification. More recently, several EU and NASA research projects focused on such aircraft configurations. Therefore, considering the available literature, the solutions which are gathering the higher research interest have been identified. In Table 2 the proposed subdivision is summarized. PFC aircraft present a conventional layout and an aft BLI propulsor, which deals with a radially-dominant distortion (360°). REC configurations display BLI engines integrated on the rear fuselage, and no split between thrust and power generation. DFC aircraft instead are characterized by several BLI propulsors and separate core engines. The BLI devices of REC and DFC present inlet pressure contours which are mainly affected by circumferential distortion (180°).

Concept	Fuselage	Core engines	Propulsor(s)	Distortion
PFC	T&W	Underwing	Single BLI	360°
REC	T&W	Rear fuselage BLI	None	180°
DFC	T&W, HWB	Rear fuselage BLI, wing tip	Multiple BLI	180°

Table 2: Concept aircraft subdivision considered in the present work.

Vehicle aerodynamics	Polars, panels, VL, CFD
Propulsion system	Blocks, ML, AD, BF, TF, CFD

Table 3: Overview on the main models adopted by the reviewed works.

In the majority of the reviewed works, the benefits of BLI were assessed through the definition of a baseline non-BLI reference aircraft. The following acronyms are used hereafter:

- SoAR: state of the art reference, corresponding to current technology level;
- 2035R: mid-term reference, provided with advanced Ultra-High By-pass Ratio (UHBR) geared turbofan, corresponding to a SoAR projected for year 2035 technology level.

1.4. Modelling approaches

The mutual influence between fuselage and engine is the key for BLI benefit exploitation, but also represents a major numerical challenge [24]. In fact, the strong integration makes the vehicle aerodynamics modelling and the propulsion system modelling two necessary steps. Increasingly complex approaches can be adopted, as summarized in Table 3. The aircraft aerodynamics is usually modelled by adopting 0D polars, panel codes, Vortex-Lattice (VL) methods, or 2D/3D CFD. The propulsion system can be modelled using 0D thermodynamic block schemes, 1D Mean-Line (ML) method, Actuator Disk (AD) or Body-Forces (BF) imposed within a 2D/3D CFD domain, Through-Flow (TF) method or 3D turbomachinery CFD.

The analysis conducted by Plas *et al.* [25] can be considered as a reference example for the propulsor system modelling under BLI conditions. The work focused on the distortion transfer through the S-duct of the SAX40 aircraft. Multi-fidelity models were employed, based on 1D Parallel Compressor (PC) linked to fan characteristics, solution of 2D integral compressible boundary layer equations, and 3D CFD calculation with a BF model. Fan and ducts losses were identified as influencing factors. Although only the high-fidelity setup provided a valid representation of the flow structure in terms of radial and circumferential distortion, the low order approaches estimated a similar trend of PSC, for different levels of ingested boundary layer.

As suggested by Hendricks [26], the airframe-propulsion modelling approaches under BLI conditions can be classified based on the coupling between aerodynamics and performance calculations. In particular, considering also the scheme proposed in Figure 3.

- Uncoupled: the boundary conditions of the two models are not iteratively converged, hence a consistent interface is not provided, and no complex interactions are captured. Nevertheless, the implementation is straightforward;

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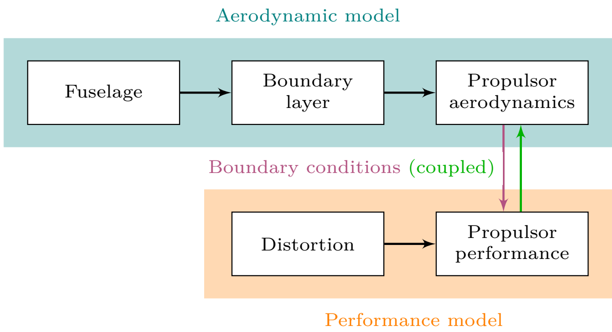

Figure 3: Schematic example of BLI aircraft modelling. The aerodynamic model and the performance model are linked through the exchange of boundary conditions.

- Coupled: physical compatibility at the boundaries is ensured by a two-way coupling between aerodynamics and performance simulations. The results of the aerodynamics model are the input to the propulsion system calculation, and these results can be used to update the aerodynamics simulation.

1.5. BLI benefit drivers

Considering the methodologies proposed in the available literature, the benefit attributed to BLI through experimental tests or numerical assessments spans a wide range indeed. In the present review, an attempt of going further in the contextualization of BLI gains dispersion has been carried out. Therefore, in order to break the estimated benefit into components, the following three benefit drivers are proposed:

- Baseline aircraft: as expressed by Equation 1, the performance variations allocated to BLI come from the comparison with respect to a baseline non-BLI aircraft. Hence the result largely depend upon this choice. Since the baseline case may differ from a study to another, results have to be taken carefully into account. A consistent analysis encompassing different configurations and comparing the expected improvements on an equivalent baseline is still missing at present. Therefore, the first diver is based on whether the two systems are equivalently defined, through one or more common benchmarks;

- Thrust-drag bookkeeping scheme: the philosophy adopted to account the BLI performance has a key influence on the results. In the present work, the power balance method [9], the exergy balance method [12] and the equivalent freestream state method [13] are recommended as consistent approaches for the analysis of BLI performance. In fact, if the near-field propulsion system inlet and exhaust flows are not expanded to the far-field, it can be difficult or impossible to estimate propulsion system ram drag. Consequently, the second driver follows the far-field approach;

- Control volume: another component which should be highlighted is the breadth of the study domain. Two main classes of analyses can be identified, namely limited to a local BLI engine design space, or extended to a global vehicle design space. The widening of the control volume can

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lead to dramatic improvements and significant cascading benefits coming from BLI integration. Nevertheless, the uncertainty of the result may rise as well. Hence, the study control volume has been pointed out in the present paper, in order to clarify the consequent assumptions and limits of each work.

Finally, the present review focuses more on the investigations on physics-based BLI benefits. Therefore, works on design integration benefits enabled by BLI have been summarized at a higher level. This distinction allows to emphasize the benefit drivers previously explained.

2. Propulsive Fuselage Concept

This layout is characterized by an aft propulsor, which encircles the rear section of a traditional T&W fuselage featuring podded engines, as sketched in Figure 4. The BLI propulsor can be either mechanically or electrically driven. An initial study of this configuration was proposed by Steiner *et al.* [23]. A top-level comparison between different aircraft concepts was assessed, and the ideal PSC was observed to drop for increasing intake area. A preliminary design study was carried out, considering electric powering of the aft-fan. The PFC was derived from a 2035R propelled by two rear-mounted podded engines through a propulsion system replacement. Following the method of Smith [8], increased mission range and intake pressure losses were calculated.

Elmiligui *et al.* [27] focused on fuselage aerodynamics, through 2D RANS simulations and sink-jet boundary conditions, but the neglected ram drag and propulsor power led to overestimated BLI benefits. Giannakakis *et al.* [20] claim an increased fuel burn, since the added mass penalty was predicted to overweight the BLI benefit. RANS simulations of the aft-fuselage and nacelle were carried out. The comparison, based on the work of Ochs *et al.* [28], was conducted at equal thrust level. Schnell *et al.* [29] followed a low-order approach, and designed the aft-propulsor using a TF code. From a sensitivity analysis, optimal pressure ratio and split ratio exist, for minimum Thrust Speficic Fuel Consumption (TSFC).

Given this open research scenario, the most interesting efforts regarding PFC concepts have been reviewed. In particular, works dealing with DisPURSAL, CENTRELINE and STARC-ABL have been analysed. A summary of the main aircraft properties is reported in Table 4. In Table 5 and Table 6 the reviewed PFC methodologies are summarized. Focus is placed on the scheme of Figure 3. Moreover, BLI fan design approach is reported, if any. Information about the BLI benefit drivers is reported.

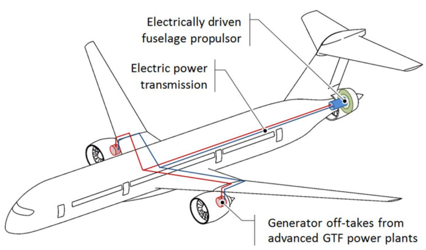

Figure 4: CENTRELINE Propulsive Fuselage Concept [17].

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	DisPURSAL	CENTRELINE	STARC-ABL
Aircraft			
Design range [km]	9000	12000	6500
Passengers	340	340	154
Cruise M [–]	0.80	0.82	0.785
MTOW [kg]	208970	211775	60092
OEW [kg]	130585	127051	35085
Block fuel [kg]	42257	-	9680
Wing span [m]	65	64	36
Fuselage length [m]	69	-	-
Podded engines			
D [m]	2.77	3.05	1.48
BPR [–]	18.1	-	-
Fuselage fan			
D [m]	4.13	2.34	1.96
BPR [–]	17.9	0	0
P [kW]	12000	8000	2610
n [rpm]	1380	-	-
$\dot{m}$ [kg/s]	-	-	-
PR [–]	1.389	1.400	1.250
PRR [–]	0.856	0.990	-
BL ingested	20.7%	19–36%	45%

Table 4: Propulsive Fuselage Concept configurations, summary of the main aircraft characteristics and propulsion design parameters [17, 23, 30–33].

2.1. DisPURSAL

DisPURSAL (Distributed Propulsion and Ultra-high By-Pass Rotor Study at Aircraft Level) was a Level-0 project of 7 European Framework Programme [33, 34]. A PFC and a DFC were designed, and no TeDP was considered. In this section, the PFC concept is analysed, whereas the DFC layout is discussed in Section 4.1. The gas turbine-driven BLI fan has the primary scope of providing wake filling. Two down-sized underwing podded geared turbofans generate the residual thrust, with a thrust split ratio equal to 77% for the podded engines [35]. However, the empennage-fan mechanical and structural integration was considered to be challenging, due to the load path disruption [36].

Isikveren *et al.* [30, 35] described the methodology employed. The preliminary aircraft sizing was defined, through CFD-based iterations and a wieght estimation. The vehicle aerodynamics was investigated performing 2D CFD analyses coupled to AD models. Later, Kaiser *et al.* [37] adopted this CFD setup to compare results from a quasi-analytical design method, and PSC was predicted to decrease for increasing thrust levels. The optimal position of the fuselage fan was investigated.

Fuel burn savings were estimated with respect to a 2035R, and the reduction of cruise Mach number could lead to further reductions. The thrust-drag bookkeeping scheme adopted throughout the DisPURSAL project was developed by Seitz and Gologan [38], based on a drag breakdown model [39]. Authors claim large lift-to-drag ratio benefit and propulsion system TSFC penalty due to BLI. Nevertheless, with respect to freestream conditions, such bookkeeping artificially reduces the aircraft drag and places the ingested drag losses within the propulsion system.

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Project	Ref(s)	Baseline equivalence	Far-field bookkeeping	Control volume	Coupling	Fuselage modelling	Boundary layer modelling	Engine modelling	BLI fan modelling	BLI fan design	Distortion modelling	Other analyses
DisPURSAL	[35] [30]	No	No	Global	No	2D CFD	2D CFD	No	2D AD[a]	1D BEM	$\Delta\eta_{pol}$	
	[37]	No	No	Global	No	2D potential	2D BL eqns	No	2D AD	1D BEM	No	
	[15]	Yes	No	Global	No	0D polars	2D CFD	0D blocks	0D blocks	0D param.	No	
	[40] [41] [32]	Yes	No	Local	No	2D CFD	2D CFD	0D blocks[b]	0D blocks[b]	0D param.	$\Delta\eta_{pol}$	①
CENTRELINE	[17]	No	No	Global	No	2D CFD	2D CFD	0D blocks	2D AD	0D param.	No	③ ④
	[42]	No	No	Local	No	No	0D ΔPRR	0D blocks[b]	0D blocks[b]	0D param.	$\Delta\eta_{pol}$	① ②
	[43] [44]	–	–	Local	No	No	3D CFD[c]	No	3D CFD[c]	3D CFD[c]	No	⑤
STARC-ABL	[31]	Yes	No	Global	No	0D polars	2D CFD	1D blocks	1D blocks	No	No	
	[45]	–	–	Local	No	3D CFD	3D CFD	No	3D AD	No	No	⑥
	[46] [47]	–	–	Global	Yes	3D CFD	3D CFD	1D blocks	1D blocks	No	No	⑦
	[48]	Yes	Yes	Local	Yes	2D CFD	2D CFD	1D blocks	1D blocks	0D param.	No	

a: ducted fan model
b: based on CFD results
c: experimental test

①: thrust split
②: power offtake
③: fuselage FEM

④: electric motor
⑤: manifactured model
⑥: wing downwash

⑦: accurate distortion calculation

Table 5: Propulsive Fuselage Concept configurations, summary of the reviewed numerical methodologies for DisPURSAL, CENTRELINE and STARC-ABL projects.

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Project	Ref(s)	Baseline equivalence	Far-field bookkeeping	Control volume	Coupling	Fuselage modelling	Boundary layer modelling	Engine modelling	BLI fan modelling	BLI fan design	Distortion modelling	Other analyses
Other studies	[23]	Yes	Yes	Local	No	No	2D CFD	No	0D blocks[b]	0D param.	No	
	[49]	–	–	Local	No	3D CFD[c]	3D CFD[c]	No	3D AD[a,b]	No	No	
	[27]	No	No	Local	No	2D CFD[c]	2D CFD[c]	No	Sink-jet BC	No	No	
	[50] [51]	Yes	Yes	Local	No	3D CFD	3D CFD	1D blocks	3D AD	No	No	
	[52]	Yes	No	Local	No	3D CFD	3D CFD	1D blocks	3D BF[b]	2D TF	No	
	[20]	Yes	Yes	Local	No	2D CFD	2D CFD	1D blocks	1D blocks	0D param.	$\Delta\eta_{pol}$	②
	[29]	Yes	No	Local	No	No	1D flat plate	0D blocks	2D TF	2D TF	No	①
	[53]	Yes	Yes	Local	Yes	3D CFD	3D CFD	No	3D CFD	3D CFD	No	

a: ducted fan model
b: based on CFD results
c: experimental test
①: thrust split
②: power offtake

Table 6: Propulsive Fuselage Concept configurations, summary of the reviewed numerical methodologies for other studies.

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Seitz and Gologan [15] performed the aircraft sizing in BLI and non-BLI conditions, adopting previous CFD simulations [23]. BLI propulsive efficiency decreased more significantly with specific thrust, compared to podded engines, hence PSC showed a stationary point with respect to intake height. Proportionality between the over-velocities reduction and the amount of boundary layer ingested was stated.

Bijewitz *et al.* [40, 41] performed a preliminary design space exploration of the BLI engine. Intake area, intake PRR and fan PR were identified as driving parameters. Furthermore, the propulsion performance model was improved with CFD-derived PRR effects [35]. The effect of penalized transmission efficiency with respect to a geared turbofan was confirmed. In a later work [32], further fuel burn savings were obtained from the removal of the common core hypothesis, and the optimal thrust split ratio decreased from 18% to 12.8%.

2.2. CENTRELINE

The CENTRELINE (ConcEpt validatioN sTudy foR fusElage wake-filLIng propulsioN intEgration) project, part of the EU Horizon 2020 programme, continues the research started within DisPURSAL, focusing on the electrically-driven PFC reported in Figure 4. Reduction of aero-structural complexity, intake losses and distortion intensity are expected [17, 33].

Seitz *et al.* [17] summarized the methodology employed within the project. The Airbus A330-300 was identified as SoAR, from which the 2035R was conceptually derived. The PFC design space was explored, adopting a 2D TF code for the initial and iterative definition of the fuselage shape. The fan was modelled through an AD, and 2D CFD simulations of the fuselage were carried out. CFD-based drag data were elaborated through the thrust-drag bookkeeping scheme adopted within DisPURSAL research studies, and a preliminary aero-structural design and integration was performed [54].

Bijewitz *et al.* [42] focused on the parametric study of the underwing engines subject to large power offtakes and different levels of thrust setting. The engine model developed within the DisPURSAL project was used [32], including the BLI fan drag in the internal thrust-drag bookkeeping scheme. The influence of intake PRR and fan PR was highlighted.

Pardo *et al.* [43] presented the core of CENTRELINE project, which is an experimental test campaign of the complete layout and of the BLI propulsor. Regarding the BLI test, two sets of stages were designed and manufactured, one optimised for clean flow, representative for the podded engines, and another for the distortion-tolerant fuselage fan. As discussed by Pardo and Hall [44], the BLI fan was characterized by a re-alignment of leading edge and stagger angles, in order to improve incidence and loading. Then, the work distribution was chosen focusing on a midspan-loaded blade, since BLI tends to increase hub diffusion factors. Moreover, negative incidence was sought towards tip, in order to reduce the tip loading and to grant an higher operability range. In the end, the increased diffusion factor at midspan was controlled through a chord variation. These flow features were checked through experimental testing and single-passage 3D CFD simulations. Improved efficiency and pressure rise towards stall was found for the BLI fan.

2.3. STARC-ABL

Moving to NASA efforts, the STARC-ABL (Single-aisle Turboelectric Aircraft with Aft Boundary-Layer propulsion) concept features a layout similar to CENTRELINE. Collecting experience from SUGAR project [55], the initial study was carried out by Welstead and Felder [31]. A mission profile estimated through FLOPS was imposed to the reference and the BLI aircraft. The vehicle aerodynamics was based on modified drag polars, and a drag breakdown scheme was employed [56]. A CFD-based boundary layer profile was normalized and used in different flight conditions, and the 1D engine model was based on the GE hFan. A preliminary sizing of the electric system resulted in a thrust split for the BLI fan of 20% at take-off and 45% at top-of-climb. Wing area and sea level static thrust per engine were identified as the driving parameters for the design space definition. The authors concluded that block fuel was more sensitive to thrust rather than to wing area, compared to a non-BLI configuration.

Kenway and Kiris [45] focused on the reduction of the inflow distortion through an aerodynamic shape optimisation of fuselage and intake. The downwash effect of the wing was observed to influence the distortion intensity. Further efforts aimed were carried out by Ordaz *et al.* [47] and Ordaz [46], employing a coupling between propulsion and vehicle modelling. The importance of coupling was highlighted in the increased ram drag calculated, with respect to the propulsion system alone.

Gray *et al.* [48] proposed a methodology based on the coupling between 1D propulsor model and 2D RANS aerodynamic calculations within an optimisation framework. The net horizontal force was computed, for BLI and podded layouts, for equal shaft power. BLI effects were accounted through the analytical definition of viscous, pressure and momentum flux forces on the aircraft within the RANS solver.

Sadey *et al.* [57] proposed a model for power system preliminary sizing, and Yoon *et al.* [58] defined several motor concepts for the aft-fuselage fan. Kratz and Thomas [59] stated that neglecting system dynamics and control strategy could lead to an over-designed propulsion system, with a 3% excess in the high-pressure compressors stall margin.

2.4. Other studies

A part from the examined research projects, additional works involved the numerical modelling of PFC propulsion systems. Atinault *et al.* [49], within RAPRO2 project by ONERA, validated a methodology for the estimation of BLI potential by adopting both experimental and numerical approaches. Following the steps of RAPRO1 project, 3D CFD calculations were carried out. The BLI benefit was calculated as the reduced power impressed by the device to the flow with and without BLI, and positive results were observed.

Blumenthal *et al.* [50, 51] considered the NASA Common Research Model geometry, and performed a CFD analysis considering the semi-span aircraft geometry Boundary conditions at the nacelle faces were linked to a 1D NPSS model based on GE90-115B engine. The BLI case was simulated by adding an AD downstream of the empennage, and the aft-fuselage geometry was iteratively adjusted. The post processing of the CFD analysis at equal axial force and mass flow followed the power balance

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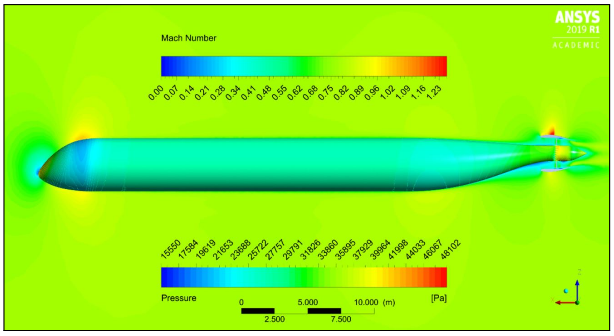

Figure 5: Mach number contour around a full-annulus aft-fan propulsor [53].

method. A reduced power requirement at cruise was highlighted, and the greater benefit came from the reduced incoming velocity. Nevertheless, no weight penalties were taken into account.

Lee *et al.* [52] proposed a multi-fidelity approach. A 2D TF method was employed for the fan design, whereas 3D CFD was adopted for single-passage fan-stator interaction and vehicle aerodynamics simulations. Moreover, a BF model was included [60]. The authors proposed to decouple the design of fuselage, inlet and nacelle design from the remaining propulsor components, since the upstream flow is not influenced by the BLI fan installation. The GE-R4 fan was selected for the validation, and a fuel burn benefit was assessed at equal thrust and power.

Fernández and Smith [53] studied a PFC based on an Airbus A320 layout with an electrically-driven fan. A CFD approach was followed, considering isolated and integrated simulations. The former was adopted as the non-BLI setup. In Figure 5 a Mach number contour around the full-annulus coupled configuration is shown. The CFD-based forces acting on the bodies were integrated for the BLI benefit assessment, and lower drag and higher propulsive force were observed.

3. Rear Engines Concept

An intermediate class of aircraft is presented in this section, characterized by a T&W fuselage and no separation between thrust and power producing components. Moreover, the two turbofan engines are moved from the underwing podded position to the rear zone of the fuselage. No turbo-electric propulsion is considered. The fuselage often presents morphological improvements, in order to provide an enhanced lift. The relevant research projects regarding this concept are D8 and NOVA. A summary of the vehicle and propulsion system main details is given in Table 7. Similarly to PFC, the methodologies adopted in the reviewed works are reported in Table 8.

3.1. D8

This concept, developed by MIT and NASA within the N+3 Program, features a high-lift twin-aisle fuselage, with upturned nose, referred as double-bubble. Two propulsors are installed on the flat rear end surface, and a pi-tail configuration is considered. The geometric layout is sketched in Figure 6. The rear installation of the BLI engines is beneficial, since it provides flow alignment, tail area reduction and noise shielding.

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	D8	NOVA
Aircraft		
Design range [km]	5500	5500
Passengers	180	180
Cruise M [–]	0.78	0.82
MTOW [kg]	48648	-
OEW [kg]	-	-
Block fuel [kg]	7284	-
Wing span [m]	35.8	38.1
Fuselage length [m]	37.9	44
Core engines		
D [m]	1.85	2.16
BPR [–]	20	16
P [kW]	-	-
n [rpm]	-	-
$\dot{m}$ [kg/s]	-	209[a]
PR [–]	1.47	1.40
BL ingested	9–14%	40%

a: per unit area

Table 7: Rear Engines Concept configurations, summary of the main aircraft characteristics and propulsion design parameters [13, 23, 61–64].

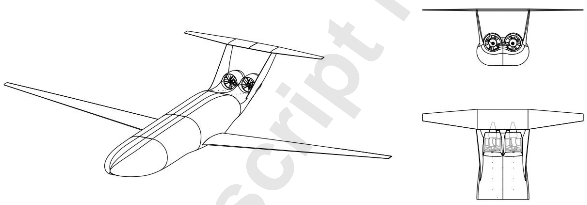

Figure 6: D8 Rear Engines Concept [65].

The concept was introduced by Drela [66], who carried out a preliminary vehicle optimisation using TASOPT multidisciplinary design and optimization tool. In particular, a 2D CFD code allowed the drag estimation, and BLI benefits were weighted through a power balance method, which was implemented within in the software. Moreover, the method was adopted also in the following works on D8. The aerodynamic analysis was aided by VL codes and panel codes. Considering a modified Boeing 737-800 as reference, a morphing re-design approach was employed, in order to divide the evolution of the BLI solution from the baseline aircraft into several steps. A low-speed wind tunnel test was also carried out, confirming the numerical analysis in terms of lift-to-drag ratio.

Pandya [67, 68] assessed the BLI benefit of the D8 concept through a CFD modelling. As reference non-BLI configuration, the same engines were placed in podded position on the aft-fuselage sides. The comparison, carried out at equal axial force pointed out a reduction in mechanical power. Based on the same test cases, Uranga *et al.* [64, 65, 69] conducted further experimental and numerical assessments. Analyses at equal nozzle area and equal mass flow were carried out, and the BLI solutions showed less cruise power consumption. This benefit was attributed 57–69% to reduced jet dissipation, 23–38% to reduced airframe dissipation, and 5–8% to lower wake dissipation.

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Project	Ref(s)	Baseline equivalence	Far-field bookkeeping	Control volume	Coupling	Fuselage modelling	Boundary layer modelling	Engine modelling	BLI fan modelling	BLI fan design	Distortion modelling	Other analyses
D8	[66]	Yes	Yes	Global	No	$2D^{a,b}$	$2D^{a,b}$	1D blocks	1D blocks	No	No	
	[67] [68]	Yes	Yes	Local	No	3D CFD	3D CFD	No	3D AD	No	No	
	[65] [69] [64]	Yes	Yes	Local	No	Exp.	Exp.	No	No	No	No	
	[63] [70]	Yes	Yes	Global	No	$3D\ CFD^{b}$	3D CFD	1D blocks	1D blocks	No	$\Delta\eta_{pol}$	
	[71] [72] [73]	Yes	Yes	Global	No	0D polars	No	1D blocks	1D blocks	No	$\Delta\eta_{pol}$	①
NOVA	[61] [62]	Yes	Yes	Global	No	3D CFD	3D CFD	0D blocks	3D AD	No	No	
	[74] [75]	–	–	Local	No	3D CFD	3D CFD	No	No	No	No	①
	[76] [77]	–	–	Local	No	No	3D CFD	No	3D CFD	No	No	①
Other studies	[78]	Yes	Yes	Local	No	2D/3D CFD	2D/3D CFD	No	2D/3D AD, BF	No	No	
	[79] [80]	–	–	Local	No	No	3D CFD	No	3D CFD	No	No	②

a: viscous-inviscid CFD, panels
b: experimental test
c: based on CFD results
①: acoustics
②: fan FEM

Table 8: Rear Engines Concept configurations, summary of the reviewed numerical methodologies for D8 and NOVA projects as well as other studies.

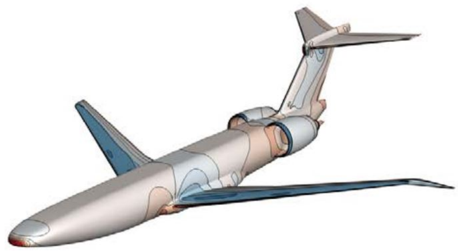

Figure 7: NOVA Rear Engines Concept [61].

Yutko *et al.* [63] carried out a conceptual system-level analysis. They considered a D8 featuring 2016 technology level, and a Boeing 737-800 as reference aircraft, with common mission profile requirement. TASOPT and FLOPS were employed for aircraft geometry and weight estimation, and CFD analyses of the fuselage aerodynamics were performed focusing on nose and tail configurations. An experimental comparison was included [70]. The Aurora in-house propulsion system tool was chosen for the performance evaluation, and fuel burn savings compared well to TASOPT predictions.

Marien *et al.* [71] investigated a variant of the D8 concept. An optimisation framework was used to connect OpenVSP and FLOPS software, for geometry, aerodynamics, weights and mission performance calculations. A power balance method was considered, and the comparison against the podded configuration showed reduced fuel burn. Further acoustic analyses were performed by Clark *et al.* [72, 73].

3.2. NOVA

A REC concept is currently being studied by ONERA, within the NOVA (Nextgen ONERA Versatile Aircraft) project, targeting 2025 as entry-into-service year. The goal is to perform fluid dynamics and acoustic numerical simulation of the full aircraft geometry featuring BLI engines. The vehicle geometry, characterized by a wide-body high-lift fuselage, is reported in Figure 7.

The first study was proposed by Wiart *et al.* [61, 62]. After the preliminary fuselage sizing, the 3D geometry was simulated through RANS calculations, and ONERA ffd72 far-field drag extractor was adopted to post-process results. A configuration featuring podded engines on the rear fuselage sides served as non-BLI case, whereas for the BLI configuration the engines were partially embedded into the fuselage, while keeping fan diameter and nozzle area. The fan was modelled through an AD approach, and the simulation predicted a lower wake intensity.

Mincu *et al.* [74] and Lorteau *et al.* [75] investigated the potential of noise shielding for the NOVA aircraft through 3D RANS simulations of the aircraft. A noise reduction was observed ahead of the aircraft, whereas similar levels were observed behind. Further acoustic analyses were recently proposed by Romani *et al.* [76, 77]. The BLI configuration introduced by Wiart *et al.* [61] was provided with the low-noise NASA SDT fan stage. 3D Lattice-Boltzmann calculations were performed for the flow around the engine in BLI and non-BLI conditions. Fan efficiency and pressure ratio losses were observed, and the noisiness levels lower towards ground direction compared to the isolated case.

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3.3. Other studies

Wiart and Negulescu [78] proposed the Airbus Nautilus configuration as a development of the NOVA aircraft, in order to maximize the portion of ingested boundary layer. The engines were moved to the most downstream location, adopting an installation close to PFC configuration. A 2D CFD approach was followed together with a 2D AD and and BF models implemented within the elsA solver from ONERA. In order to point out the BLI effect, a reference non-BLI configuration of the fuselage and an isolated engine were also simulated, and a power saving was estimated through power balance.

Within the DLR project AGATA, Diouf *et al.* [79] performed an experimental and numerical analysis of the CRISPMulti, a counter-rotating ducted fan, designed for clean inflow. Starting from previous DLR high-fidelity simulations, a steady single-passage CFD analysis was performed, and unsteady solutions were calculated through harmonic balance methods. In a successive work, Eichner *et al.* [80] focused on the aeroelastic effect of BLI on fan blades of the same test case. The flow field solution provided the input for the structural analysis, and a relevant but not dominant contribution to fatigue was detected.

4. Distributed Fans Concept

Moving to more challenging BLI aircraft layouts, the DFC currently represents the most synergistic propulsion-airframe integration solution. The fuselage is characterized by blended-wing and HWB shapes. The thrust generation is handled by multiple embedded propulsors. TeDP is often employed, through the installation of several electrically-driven fans, powered by a limited number of cores [16]. Alternatively, a gear-driven multiple fan configuration can be considered [14]. Such propulsion assembly is characterized by circumferential inlet flow distortion, which is estimated to cause 2–3% loss in fan efficiency and a reduction in surge margin [81].

The main limitation of this concept is inherent in the fuselage-engine integration, which is often disruptive and needs a huge technological improvement. Nevertheless, enhanced spanwise lift, super-circulation and boundary layer control allow short take-off and landing operations, along with reduced weight and noise [14]. Moreover, high by-pass ratios can be achieved, while keeping the superior efficiency of large core engines, which are decoupled from the TeDP. Furthermore, a propulsion-based control allows the downsizing of the empennage surfaces.

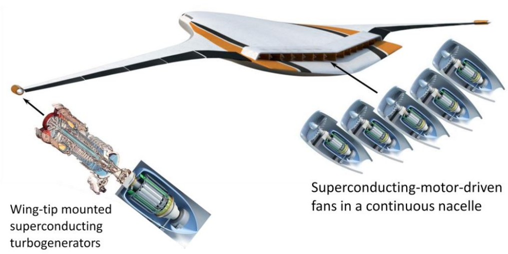

Figure 8: N3-X Distributed Fans Concept [82].

The research projects reviewed here are DisPURSAL, N3-X and DRAGON. A summary of the characteristics of vehicle and propulsion system is reported in Table 9. Following the same scheme proposed for PFC and REC, the methodologies regarding DFC configurations are summarized in Table 10 and Table 11.

	DisPURSAL	N3-X	DRAGON
Aircraft			
Design range [km]	8900	13900	2200
Passengers	340	300	150
Cruise M [–]	0.80	0.84	0.78
MTOW [kg]	206540	214776	-
OEW [kg]	127240	109252	-
Block fuel [kg]	38960	38552	-
Wing span [m]	65	64.9	-
Fuselage length [m]	37	41	-
Core engines			
D [m]	1.88	-	-
BPR [–]	20	-	-
Distributed fans			
D [m]	-	1.04	-
P [kW]	-	2983	1000
n [rpm]	-	4947	-
$\dot{m}$ [kg/s]	-	1133.98[a]	-
PR [–]	-	1.26	1.40
BL ingested	10.5%	11–20%	6–16%

a: cumulative for the propulsors array

Table 9: Distributed Fans Concept configurations, summary of the main aircraft characteristics and propulsion design parameters [23, 30, 33, 36, 82, 83].

4.1. DisPURSAL

As discussed in Section 2.1, a DFC layout was analysed within the DisPURSAL project. On the rear end of a HWB fuselage, a couple of propulsion modules are installed on the upper surface, at the sides of the centreline, composed of a core engine and two mechanically-driven fans. The research methodology presented by Isikveren *et al.* [30, 35] and analysed previously was applied also for the DFC study. The 2D geometry considered was a representational section of the HWB fuselage, corresponding to the most outboard fan axis. No core flow was simulated. The influence of incidence angle and fan PR was investigated. In particular, higher PR determined significant effects on Mach number distribution over the fuselage, and a reduction of boundary layer thickness ingested by the engine. Mach number and lift decreased for higher fan diameters. Starting from previous CFD simulations [84], a comparison was carried out in order to assess BLI benefits. A surge margin degradation was observed, along with a fan efficiency drop. Consistent lift-to-drag ratio benefit and TSFC penalty were attributed to BLI. However, as discussed for the PFC configuration, this result is generated by the thrust-drag bookkeeping scheme used [15].

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Project	Ref(s)	Baseline equivalence	Far-field bookkeeping	Control volume	Coupling	Fuselage modelling	Boundary layer modelling	Engine modelling	BLI fan modelling	BLI fan design	Distortion modelling	Other analyses
DisPURSAL	[35]	No	No	Global	No	2D CFD	2D CFD	No	2D AD[a]	1D BEM	$\Delta\eta_{pol}$	
	[30]	No	No	Global	No	2D CFD	2D CFD	0D blocks	2D AD[a]	1D BEM	PC	
	[85]	Yes	Yes	Local	No	2D CFD	2D CFD	No	2D AD	No	$\Delta\eta_{pol}$	①
N3-X	[82]	Yes	–	Global	No	No	3D CFD	1D blocks	1D blocks	No	$\Delta\eta_{pol}$	②
	[86] [60]	–	–	Global	No	3D CFD	3D CFD	No	3D BF[b]	No	No	
	[87] [88]	–	–	Global	No	No	1D flat plate	1D blocks	1D blocks	1D blocks	$\Delta\eta_{pol}$	
	[81]	–	–	Local	No	No	1D flat plate	No	1D ML[c]	1D ML	No	
DRAGON	[83]	Yes	–	Global	No	2D CFD	2D CFD	No	No	No	No	③

a: ducted fan model
b: based on CFD results
c: enhanced discretization
①: aerothermopropulsion
②: electric motor
③: wing FEM and aeroelasticity

Table 10: Distributed Fans Concept configurations, summary of the reviewed numerical methodologies for DisPURSAL, N3-X and DRAGON projects.

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Project	Ref(s)	Baseline equivalence	Far-field bookkeeping	Control volume	Coupling	Fuselage modelling	Boundary layer modelling	Engine modelling	BLI fan modelling	BLI fan design	Distortion modelling	Other analyses
Other studies	[89]	Yes	No	Local	Yes	3D CFD	3D CFD	1D blocks	1D blocks	No	No	
	[90] [91] [92] [93]	Yes	Yes	Local	No	No	3D CFD	1D blocks	3D CFD	3D CFD	PC	④
	[94]	–	–	Local	No	No	1D flat plate	0D blocks	0D blocks	No	PC[d]	
	[95] [96]	–	–	Local	No	No	Exp.	No	3D CFD[e]	3D CFD[e,f]	No	⑤
	[97]	–	–	Local	No	No	3D CFD	No	3D TF	3D TF[f]	No	
	[28]	Yes	Yes	Local	No	No	3D CFD	1D blocks	3D CFD	No	No	
	[98] [99] [100] [101]	–	–	Local	No	No	3D CFD[e]	No	3D CFD[e]	3D CFD[e]	No	④
	[102]	–	–	Local	No	No	1D flat plate	No	2D TF[b,g]	2D TF[b,g]	No	
	[103]	Yes	Yes	Global	No	3D lifting surf.	2D panel	0D blocks	0D blocks	0D param.	PC	

b: based on CFD results
d: coupled to parallel stream method
e: experimental test
f: parametric re-design
g: streamtube model
④: fan flutter
⑤: manifactured model

Table 11: Distributed Fans Concept configurations, summary of the reviewed numerical methodologies for other studies.

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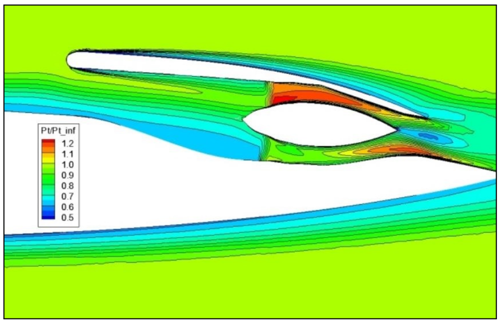

Figure 9: Normalized total pressure contours of N3-X BLI propulsor, modelled using a BF model, $M = 0.84$ [86].

Arntz and Atinault [85] analysed the configuration by applying the exergy balance method. A 2D representative model of the airframe was considered, and the aerodynamics was investigated through RANS simulations. The propulsor was modelled inside the 2D nacelle using an AD. A reduced wake exergy dissipation was estimated, compared to the unpowered case. The temperature difference between wall and fluid can lead to further improvements.

4.2. N3-X

The DFC configuration proposed by NASA is one of the most ambitious BLI aircraft concepts, featuring a HWB fuselage and TeDP layout. The thrust is provided by several ducted fans installed on top rear fuselage, as represented in Figure 8. Electrical power is generated by two wingtip-mounted turbofan engines, which operate under undisturbed free-stream conditions, producing the minimum required thrust to avoid being a drag source, thus reducing the core jet exhaust velocity and noise [33]. This aircraft promises significant fuel saving potential, but it is considered a long-term goal [16, 21].

The design was proposed by Felder *et al.* [82]. 1D NPSS models and FLOPS were used to simulate engines and vehicle aerodynamics, considering also previous 3D CFD calculations of a similar fuselage. SoAR and 2035R were respectively a Boeing 777-200LR and an intermediate N3-X propelled by UHBR overwing engines. A common mission profile was considered, and fuel savings were predicted due to TeDP. A minimal intake pressure loss, together with strong noise shielding effects. Technical challenges arose from the hypothesis of cooled superconducting motors, leading to a range of predicted TSFC.

Kim and Liou [60, 86] developed a multi-fidelity methodology based on a BF model, initialized through 3D CFD-based results of the GE-R4 fan rotor passage. The BF was implemented within a RANS domain, and the vehicle aerodynamics was investigated. The total pressure contour on a normal plane crossing the most outboard ducted fan is reported in Figure 9.

Laskaridis *et al.* [87] and Goldberg *et al.* [88] presented a top-level exploratory study on TeDP concept. Fuselage geometry, boundary layer and distortion impact were modelled using multi-fidelity approaches. The electrical equipment sizing was included. Results showed that the intake pressure losses play a dominant role for low pressure ratios, low specific thrusts and high mass flows.

Valencia *et al.* [81] proposed a semi-empirical approach to model the effects of BLI on fan performance. A traditional 1D Mean-Line (ML) clean design was performed, and a discretized approach was proposed for the analysis under distortion. Therefore, a loss in fan efficiency was calculated.

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4.3. DRAGON

A different DFC approach was considered by ONERA in the definition of the DRAGON (Distributed fans Research Aircraft with electric Generators by ONERA) concept, funded by EU Clean Sky 2 Program, and gathering knowledge from the previous project AMPERE. As described by Schmollgruber *et al.* [83], this solution features an array of ducted electrical fans along the wingspan, powered by two podded turbofan engines, placed on the rear fuselage sides. The fans are aligned in the compression zone of the wing trailing edge. Therefore, no engine-shock coupling is present. Nevertheless, this position is not favourable in low speed conditions, and a propulsive flap solution was suggested.

Preliminary 2D CFD simulations of the wing airfoil coupled to an underwing fan were carried out, and initial geometrical shaping and definition of the design space were assessed. An increased wing weight was found, although FEM analyses computed a bending moment benefit. A 2035R baseline was defined for the same mission profile, and a reduced fuel burn was observed.

4.4. Other studies

Regarding other studies dealing with DFC concept, Rodriguez [89] focused on multidisciplinary optimization of BLI inlets. Two HWB were considered, with rear podded engines and BLI engines. 3D CFD simulations and 1D engine modelling were integrated into an optimization tool. Higher aerodynamic efficiency but also higher fuel burn were estimated, due to intake losses. The author followed a thrust-drag bookkeeping scheme based on CFD-based drag breakdown.

The NASA Robust Design for Embedded Engine Systems (RDEES) program focused on BLI engine design methodology. Hardin *et al.* [90] performed a high-level research, considering Boeing N2A-EXTE HWB aircraft as reference. CFD-based boundary conditions profile provided the input to a 1D NPSS engine model. Following a far-field bookkeeping scheme, a reduction in fuel burn was estimated at equal thrust conditions. Florea *et al.* [91, 92] focused on the CFD optimization of the inlet, in order to reduce distortion and intake losses. Moreover, Bakhle *et al.* [93] proposed the aeroelastic analysis of the fan, and a no flutter issues were observed.

A preliminary methodology for the distortion impact assessment was proposed by Liu *et al.* [94], through 1D fan model, PC and parallel streams implementations. The research of Gunn and Hall [95] focused on the experimental low-speed testing and RANS transonic simulation of the VITAL fan [104]. Both core and by-pass flows were simulated. Later, a non-axisymmetric design was proposed for a low-speed BLI stator [96], following a 2D sectional approach. Hall *et al.* [97] proposed a parametric design exploration, based on full-annulus CFD simulations and TF modelling of NASA R4 fan.

The NASA Boundary Layer Ingesting Inlet / Distortion Tolerant Fan (BLI^2DTF) task continued the research efforts started with RDEES. As presented by Cousins *et al.* [98] and Arend *et al.* [99], the integrated inlet-fan design was addressed. Satisfactory levels of fan stability margin where achieved, highlighting the possibility of controlling the distortion impact through a dedicated BLI fan design. The design space exploration was investigated by Ochs *et al.* [28], carrying out a CFD study of the geometry reported in Figure 10, based on previous results [105]. In order to represent a podded reference, intake and nozzle were removed. BLI benefits were assessed by expanding inlet and exhaust

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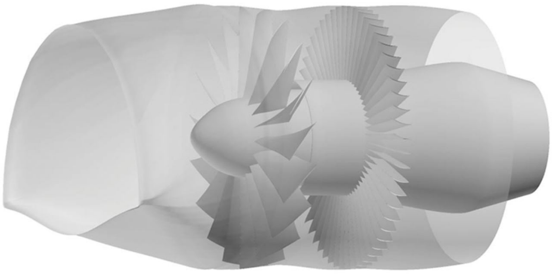

Figure 10: Geometry of the distortion-tolerant fan stage of BLI^{2}DTF program [28].

to the freestream conditions. Finally, Bakhle *et al.* [100] carried out an aeromechanics analysis of the rotor, analysing different distortion patterns by means of 3D RANS calculations. No flutter was detected, but a two-way coupling was suggested. Cases of negative damping were observed by Heinlein *et al.* [101] for the inlet-fan configuration.

Mennicken *et al.* [102] discussed propulsor design methodology based on a 2D TF code, calibrated 3D CFD simulations of several geometries. The design space of the DLR UHBR fan was explored, in order to alleviate the distortion impact, and an enhanced stability margin was calculated.

Gao and Smith [103] proposed the GENUS multidisciplinary aircraft design environment, composed by modules for geometry, mission and engine properties. In particular, the BLI module was based on XFOIL and a PC model. The Cranfield BW-11 concept was considered, and a reduced TSFC was estimated through power balance.

5. Conclusions

In the present review, the available literature regarding BLI numerical methodologies have been examined. The aircraft concepts which gathered more research interest were identified, and a number of configurations featuring BLI engines have been considered. These have been grouped into three families, namely Propulsive Fuselage Concept (PFC), Rear Engines Concept (REC) and Distributed Fans Concept (DFC), as reported in Table 2. The expected improvements of such configurations are summarized in Table 12, in terms of variation of fuel burn, thrust-specific fuel consumption and power saving coefficient, with respect to a reference non-BLI aircraft of the same technology level. Furthermore, following and expanding the leading example proposed by Steiner *et al.* [23], the distribution of the estimated benefits is reported in Figure 11. Therefore, several conclusions can be pointed out:

- Based on the BLI benefit drivers criteria pointed out in Section 1, the authors propose a qualitative subdivision into three levels of confidence, aiming to remove any potential artifact from the estimated BLI performance. In particular, the distinction is based on the first two drivers, namely reference aircraft and thrust-drag bookkeeping scheme, for which a recommended approach has been identified. Regarding the third driver, based on the study control volume, the authors suggest to use it as a guide to contextualize limitations, assumptions and numerical fidelity of each research. Further information are reported in Tables 5, 6, 8, 10 and 11;

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		Hybrid	Baseline aircraft	Fuel burn	TSFC	PSC	Benefit drivers satisfied
PFC	DisPURSAL	No	①	-13.4%	19.8%	5.6–10.4%[b]	Rarely
	CENTRELINE	Yes	①	-11.0%[a]	–	11.8%[a]	Rarely
	STARC-ABL	Yes	②	-3.4%	-2.6%	2.0–2.5%	Mostly
REC	D8	No	③	-30.1%	-11.3%	7.6–8.5%	Mostly
	NOVA	No	④	–	-15.0–20.0%[a]	4.0–5.0%	Mostly
DFC	DisPURSAL	No	①	-7.8–10.5%	10.7%	3.2–5.7%[b]	Rarely
	N3-X	Yes	⑤	-18.0–20.0%	-12.2–37.0%	3.2–5.7%[b]	Often
	DRAGON	Yes	⑥	-3.0–8.0%	-5.0–10.0%	1.6–4.7%[b]	Often

a: target value
b: from Steiner *et al.* [23]

①: Airbus A330-300, 2035R
②: Boeing 737-800, 2035R
③: D8, rear podded engines
④: NOVA, rear podded engines
⑤: N3-X, overwing engines
⑥: T&W, 2035R

Table 12: Estimated BLI benefits for the configurations considered.

- Regarding the BLI performance measured through PSC, all the configurations show an improvement. Wake filling grants a reduced power consumption in order to produce the same amount of thrust. For some configurations no PSC studies were found, hence the results of Steiner *et al.* [23] have been included;

- The adopted criteria are mostly satisfied for STARC-ABL, D8 and NOVA studies. Moreover, N3-X and DRAGON show a positive trend. Less matching is observed for DisPURSAL and CENTRELINE. Nevertheless, some projects are still ongoing;

- The increased TSFC observed within DisPURSAL project has been attributed to the behaviour of the thrust-drag bookkeeping scheme employed;

- The PFC concept is the most feasible from an engineering point of view, followed by REC concept, since realizable changes in the airframe are required. The DFC concept shows promising results, but can be considered as a future goal, as theoretical investigations are still needed. Therefore, in order to focus on near-term applications, attention should be placed on PFC and REC concepts;

- TeDP is expected to enhance BLI benefits, and such upgrade is regarded as an important step for mid-term developments. However, uncertainties on weight penalty require further investigations.

- Focusing on the BLI fan design parameters which have a major influence, the following considerations can be drawn:

  1) Intake height and engine burying level play an important role in the definition of the inlet shape. This has a direct influence on the distortion pattern and on the amount of boundary layer ingested, impacting respectively on fan performance and wake filling exploitation;

  2) Intake pressure recovery is widely recognized as a key factor influencing propulsive efficiency, and analyses combined with the specific thrust level are often suggested;

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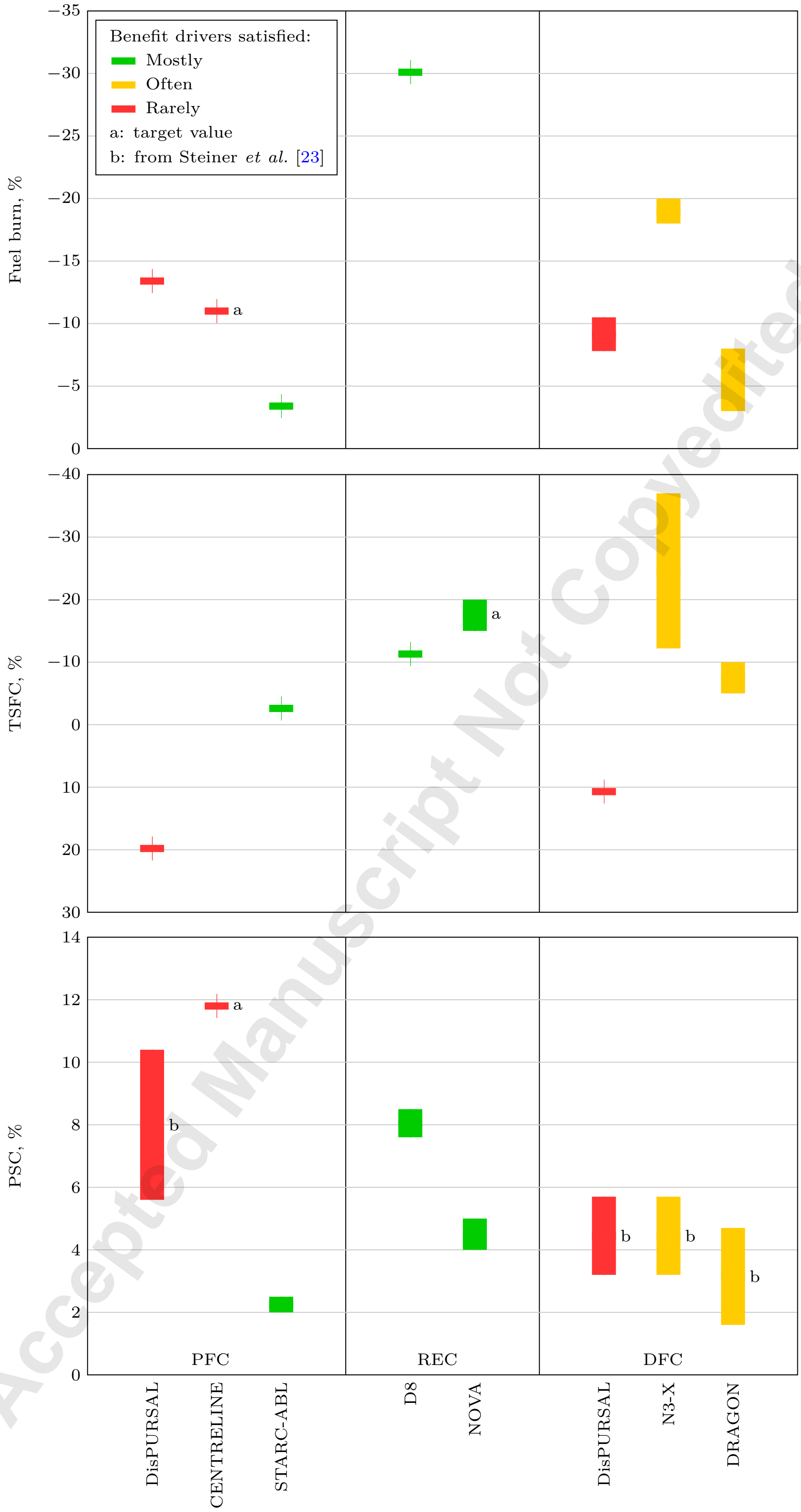

Figure 11: Estimated BLI benefits for the configurations considered. Values from Table 12.

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3) If an electrically-driven fan is considered, weight penalties have to be taken into account. Moreover, thrust split and power offtakes are fundamental parameters which influence the design of the core engines.

- The use of high-fidelity calculations combined to the predictions from low-order models appears as the most effective strategy for the analysis of integrated propulsion systems. In particular, RANS calculations are widely adopted for vehicle aerodynamics. CFD simulations can unquestionably serve as a benchmark for the engine performance analysis, although cannot be part of a preliminary design framework without the coupling to a low-order approach. Moreover, since the design space of BLI solutions is still under exploration, parametric analyses are needed. Therefore, the adoption of flexible and fast methods is recommended during this initial phase.

To conclude, the top-level analysis of BLI methodologies proposed in the present review can be further developed. In particular:

- The concept of BLI benefit drivers criteria can be expanded and quantitatively weighted;
- The creation of common guidelines for the definition of an equivalent non-BLI baseline aircraft and of a consistent thrust-drag bookkeeping is strongly suggested;
- In order to get a bigger picture of BLI studies, research works which are not linked to the guiding projects identified in this review can be further analysed. In particular, the BLI^{2}DTF program recently produced significant results in terms of distortion-tolerant fan design.

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