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The Energy-Efficient Aircraft of the Future – A Long-Term Perspective

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The Energy-Efficient Aircraft of the Future: A Long-Term Perspective

Executive Summary

With the goal of drastically reducing aviation's climate-impact footprint, and even achieving a net-zero aviation system by 2050, the aviation stakeholders face enormous challenges. While it is clear that these goals can only be achieved through the use of renewable and sustainable energy sources such as sustainable aviation fuels (SAF) and green hydrogen, there will be limitations in their availability, as well as significantly increased fuel cost associated with this energy transition. The challenges arise from the investments required for renewable energy production capabilities, infrastructure and logistics, as well as higher recurring costs due to increased production costs of SAF and hydrogen. Therefore, targeted measures to significantly enhance the energy efficiency of the air transport system are essential, addressing both transport operations and aircraft design.

In this paper, the authors focus on the latter, examining how much aircraft efficiency can be further enhanced to support these goals. To this end, various technological options are discussed with a balanced approach, considering both their potential and the challenges associated with significantly improving energy efficiency. Based on our findings we outline a pathway for achieving a reduction of *50%* or more in the energy consumption of future aircraft.

In the broad field of aircraft technologies, those are highlighted that promise the highest saving potentials in aerodynamics, airframe structures, aircraft control, propulsion systems and aircraft systems, also allowing for the derivation and assessment of promising aircraft configurations. This is complemented by identifying key enablers, name-

ly multi-disciplinary optimization, changes in aircraft certification and revised operational constraints.

The authors identify the following key technologies as candidates for viable integration into future classes of large transport aircraft well before 2050:

Aerodynamic efficiency needs to be improved through a balanced approach, combining viscous drag reduction with the reduction of induced drag. The concepts of viscous drag reduction techniques through laminar flow control are well understood but only partially demonstrated at sufficient levels of technology readiness. They will provide the highest leverage for viscous drag reduction if applied on all aerodynamic surfaces, including ideally the fuselage, for which mature solutions are still lacking. However, to fully leverage the potential, exploitation will require advances and changes to the wing design, compliant high-lift devices and the actuation and control system. Especially the latter will go hand in hand with increasing the wingspan of future aircraft to further reduce the induced drag. This will require advanced structural concepts, fully utilizing the potentials of carbon fibre composite (CFRP) structures, and advanced flight controls allowing for active load control. However, the constraints imposed by actual infrastructure standards at airports interfere with the full exploitation of aircraft with significantly higher spans than currently employed. This may be overcome by the adaptation of airport standards or by integrating new technical means like folding wingtips in future aircraft.

Airframe structures will be key enablers for further significant weight reductions, but also functional capabilities not achieved with classic designs. For this, the authors consider it essential to fully utilize the capabilities and features of CFRP materials in a thoroughly integrated and consistent manner. Due to the special characteristics of carbon fibre–based structures, some essential design requirements that were introduced to allow fail-safe designs in metallic structures are no longer valid. If suitable design requirements were adapted to the physical properties and characteristics of the material and the structural design, significant weight reductions and tailored functionalities, e.g. in the control of structural loads and flutter, would be possible.

Active control of the aircraft in combination with **advanced systems technologies** will be the key enablers to allow for functionalities like active alleviation of gust loads, manoeuvre loads and even flutter control to substantially reduce aircraft weight, and to allow the realization of wings with extremely high aspect ratios. Additionally, they may contribute to allowing new or enhanced synergies in the utilization of energy on board the aircraft. Especially if we consider hydrogen as one promising sustainable fuel option for aviation, a series of changes will be required on the systems side, including fuselage-integrated and insulated tanks, hydrogen-handling and safety systems and thermal and water management. This will also make it possible to take advantage of additional synergies, especially with new concepts for thermal management utilizing hydrogen as a coolant and along with water, integrated in hybrid architectures comprising fuel cells and gas turbines.

More synergistic approaches will also allow for enhanced efficiency in the field of **propulsion integration**. New engine concepts with an ultra-high bypass ratio or open propulsors will benefit from integration where the stronger aerodynamic coupling of the airframe aerodynamics with the propulsion flow needs to be deliberately controlled. One potential technology in this field is boundary layer ingestion (BLI), which could help to reduce the adverse effects of viscous drag on the fuselage to enhance overall propulsive efficiency. The use of process water for hydrogen-based aircraft enables significant NO_x reductions as well as efficiency improvement in the core engine.

Integrating the different technologies into a specific aircraft configuration will eventually show the integrated potential, as synergies may be utilized more or less and integration penalties may be more prominent in some combinations than in others. We also point out that top-level aircraft requirements and also varied concepts of operations with altered cruise speed and cruising altitude, as well as novel routing concepts, can have significant impacts on overall aircraft performance and need to be carefully reviewed and probably adapted for future transport networks and operations. While radically changed aircraft configurations show some specific advantages, the authors still consider an advanced tube and wing configuration as promising for achieving maximum reductions of energy consumption.

In order to quantify the identified potentials, an exemplary, yet very promising combination of technologies is provided for a future short- and medium-range (SMR) configuration and compared to a reference aircraft with an A350 technology level. The **saving potentials** are presented in detail, given the mutual interactions being key for some technologies to unfold their potential. The authors predict physically and technically sound potentials for energy savings well beyond *50%*. Even considering additional uncertainty margins used to cover present uncertainties in the technology assumptions, those savings sum up to more than *40%*.

Based on the findings presented in the paper, the authors highlight the urgent need to strengthen targeted measures to foster the identified technologies in a comprehensive and coordinated manner. Only such measures will facilitate technology maturity ready for an insertion into future products well before 2050. Boosting aircraft efficiency is seen as a key enabler to achieve the climate targets and allow for sustainable growth in the aviation sector.

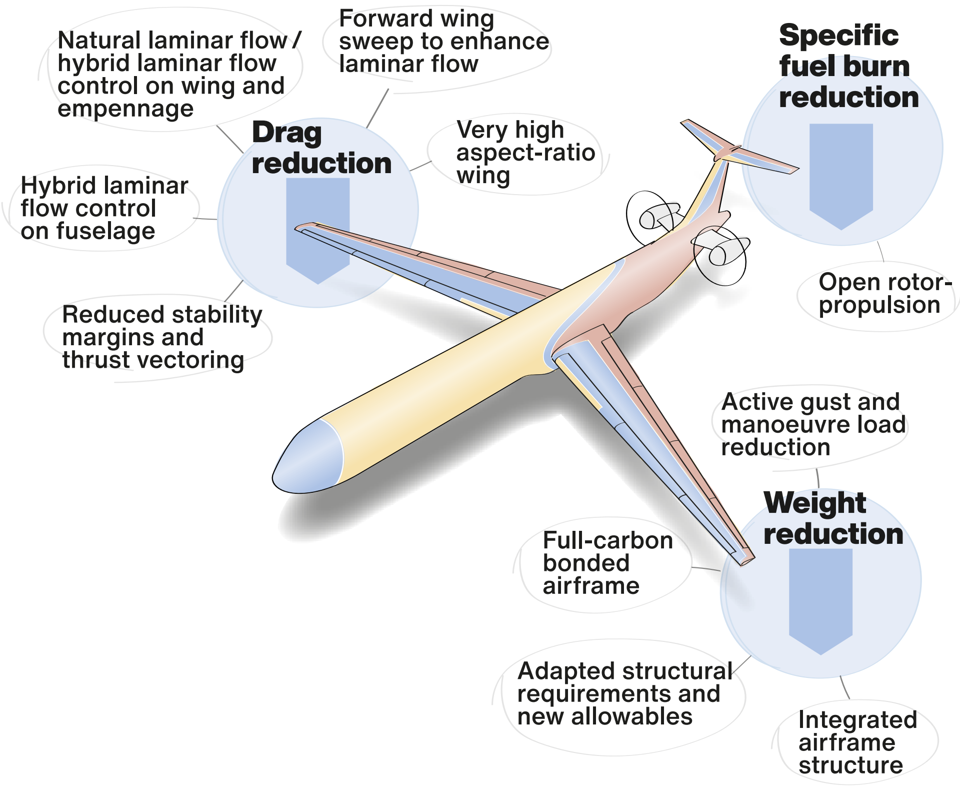

Figure 1: Key building blocks on the way to the energy-efficient aircraft of the future

Das energieeffiziente Flugzeug der Zukunft: eine Langzeitperspektive

Übersicht

Das Ziel, die Klimaauswirkungen des Luftverkehrs drastisch zu reduzieren und bis 2050 Netto-Null-Emissionen zu erreichen, stellt die Luftverkehrsbranche vor enorme Herausforderungen. Erreicht werden kann dies nur durch den Einsatz erneuerbarer und nachhaltiger Energiequellen wie nachhaltigen Flugtreibstoffen (SAF) und grünem Wasserstoff. Doch deren Verfügbarkeit bleibt auch zukünftig begrenzt und die Treibstoffkosten werden im Zuge der Energiewende erheblich steigen. Die Herausforderungen ergeben sich insbesondere aus den notwendigen Investitionen in die Produktionskapazitäten für erneuerbare Energien, die Infrastruktur und die Logistik sowie aus den höheren laufenden Aufwendungen durch die höheren Kosten für die Produktion von nachhaltigen Flugkraftstoffen und von Wasserstoff. Daher sind gezielte Maßnahmen zur deutlichen Verbesserung der Energieeffizienz des Luftverkehrssystems unerlässlich – sowohl im Verkehrsbetrieb als auch bei den Flugzeugen.

Das vorliegende Paper konzentriert sich auf die zukünftige Flugzeugentwicklung und geht der Frage nach, inwieweit die Effizienz von Flugzeugen verbessert werden kann, um die gesteckten Ziele zu erreichen. Zu diesem Zweck diskutieren die Autoren anhand eines ausgewogenen Ansatzes, der sowohl die Potenziale als auch die Herausforderungen berücksichtigt, verschiedene technologische Optionen für eine deutliche Verbesserung der Energieeffizienz. Auf dieser Grundlage skizzieren sie einen Weg, um den Energieverbrauch zukünftiger Flugzeuge um mindestens *50 %* zu senken.

Aus den vielen zur Verfügung stehenden Technologien arbeiten die Autoren die größten Einsparpotenziale aus den Bereichen Aerodynamik, Flugzeugzelle, Flugzeugsteuerung, Antriebssysteme und Flugzeugsysteme heraus, die zudem eine Ableitung und Bewertung vielversprechender Flugzeugkonfigurationen ermöglichen. Parallel dazu identifizieren sie die zentralen Faktoren, die für eine Umsetzung nötig sind. Dazu zählen die multidisziplinäre Optimierung, Änderungen bei der Zulassung von Luftfahrzeugen und überarbeitete betriebliche Anforderungen.

Als Kandidaten für eine praktikable Integration in große Verkehrsflugzeuge bis 2050 benennen die Autoren folgende Schlüsseltechnologien:

Die **aerodynamische Effizienz** eines zukünftigen Flugzeugs muss durch einen ausgewogenen Ansatz verbessert werden, der den Reibungswiderstand verringert und den induzierten Widerstand reduziert. Die Konzepte zur Verringerung des Reibungswiderstands durch laminare Strömungskontrolle sind gut erforscht, aber nur teilweise mit einem ausreichenden technologischen Reifegrad verfügbar. Sie bieten den größten Hebel zur Verringerung des Reibungswiderstands, wenn sie auf allen aerodynamischen Oberflächen zum Einsatz kommen – im Idealfall auch am Rumpf, für den es derzeit noch keine ausgereiften Lösungen gibt. Um das Potenzial voll auszuschöpfen, sind Fortschritte und Änderungen bei der Tragflächenkonstruktion, den Hochauftriebssystemen sowie den Systemen zur Kontrolle der aerodynamischen Lasten und der Flugdynamik erforderlich. Vor allem Letzteres wird mit einer Erhöhung der Spannweite zukünftiger Flugzeuge einhergehen, um den induzierten Widerstand zu verringern. Dies erfordert fortschrittliche Strukturkonzepte, die das Potenzial von Kohlenstofffaserverstärkten Kunststoffen (CFK) vollständig ausnutzen, sowie fortschrittliche Flugsteuerungssysteme, die eine aktive Lastkontrolle ermöglichen. Die Beschränkungen durch die derzeitigen Standards für die Flughafeninfrastruktur verhindern jedoch den umfassenden Einsatz von Flugzeugen mit einer wesentlich größeren Spannweite als die der aktuellen Modelle. Dazu müssten Flughafenstandards angepasst oder neue technische Möglichkeiten wie klappbare Flügelspitzen in zukünftige Flugzeuge integriert werden.

Die **Struktur der Flugzeugzelle** birgt Potenzial für weitere signifikante Gewichtsreduzierungen, aber auch für funktionale Eigenschaften, die mit klassischen Konstruktionen nicht erreicht werden können. Hierzu ist es aus Sicht der Autoren unerlässlich, die Möglichkeiten und Eigenschaften von CFK-Werkstoffen konsequent und konsistent auszuschöpfen. Aufgrund der besonderen Eigenschaften von Strukturen auf Kohlenstofffaserbasis sind einige der bisherigen Anforderungen nicht mehr zutreffend, da diese eingeführt wurden, um bei metallbasierten Strukturen ausfallsichere Konstruktionen zu ermöglichen. Eine Anpassung der Konstruktionsanforderungen an die physikalischen Eigenschaften und Merkmale des CFK-Werkstoffs und an die strukturelle Auslegung kann zu erheblichen Gewichtseinsparungen und maßgeschneiderten Funktionalitäten beitragen, z. B. zur Kontrolle von Strukturbelastungen und Flattern.

Die **aktive Steuerung** des Flugzeugs in Verbindung mit **fortschrittlichen Systemtechnologien** wird wesentliche Voraussetzungen schaffen, um Funktionen wie die aktive Reduzierung von Manöver- und Böenlasten oder auch die Flatterkontrolle zu ermöglichen. So können das Gewicht des Flugzeugs reduziert und Flügel mit extrem hohen Flügelstreckungen realisiert werden. Eine aktive Steuerung kann zudem neue oder größere Synergien bei der Nutzung von Energie an Bord erschließen. Insbesondere die Verwendung von Wasserstoff als eine vielversprechende nachhaltige Treibstoffoption für die Luftfahrt erfordert eine Reihe von systemseitigen Änderungen. Dazu gehören in den Rumpf integrierte und isolierte Tanks, Wasserstoffhandhabungs- und Sicherheitssysteme sowie ein Wärme- und Wassermanagement. Das kann zu zusätzlichen Synergien führen, insbesondere im Wärmemanagement, bei denen Wasserstoff zum einen als Kühlmittel und zum anderen zusammen mit Wasser in Hybridarchitekturen aus Brennstoffzellen und Gasturbinen eingesetzt wird.

Mehr synergetische Ansätze ermöglichen auch eine höhere Effizienz in der **Antriebsintegration**. Zukünftige Triebwerkskonzepte können extrem hohe Nebenstromverhältnisse haben oder offene Propulsoren aufweisen. Diese erfordern eine sorgfältige Integration, da die stärkere aerodynamische Kopplung der Zellenaerodynamik mit der Umströmung des Antriebs ausgenutzt werden muss. Eine mögliche Technologie in diesem Bereich ist die Boundary Layer Ingestion (BLI), die zur Verringerung der negativen Auswirkungen des viskosen Widerstands am Rumpf und damit zur Verbesserung der Gesamteffizienz des Antriebs beitragen könnte. Die Verwendung von Nutzwasser in wasserstoffbetriebenen Flugzeugen ermöglicht eine erhebliche NO_x-Reduzierung sowie einen verbesserten Wirkungsgrad des Haupttriebwerks.

Die Integration der verschiedenen Technologien in eine bestimmte Flugzeugkonfiguration wird letztendlich das volle Potenzial aufzeigen. Je nach Konfiguration können Synergien mehr oder weniger genutzt werden und Nachteile fallen bei einigen Konfigurationen stärker ins Gewicht als bei anderen. Die Autoren weisen darauf hin, dass die Definition der Top Level Aircraft Requirements (Maßgebliche Forderungen an die Flugzeugeigenschaften) ebenso wie unterschiedliche Betriebskonzepte mit veränderten Reisegeschwindigkeiten und Reiseflughöhen sowie neuartige Streckenführungskonzepte erhebliche Auswirkungen auf die Gesamtleistung von Flugzeugen haben können. Dies sei sorgfältig zu prüfen und gegebenenfalls an künftige Verkehrsnetze und -abläufe anzupassen. Obwohl radikal geänderte Flugzeugkonfigurationen einige spezifische Vorteile bieten, sind die Autoren davon überzeugt, dass fortschrittliche „Tube-and-Wing"-Konfigurationen weiterhin vielversprechend sind, um maximale Energieeinsparungen zu erzielen.

Um die genannten Potenziale zu quantifizieren, wird eine beispielhafte und vorteilhafte Kombination von Technologien für eine künftige Kurz- und Mittelstreckenkonfiguration (Short- and Medium-Range, SMR) vorgestellt und mit einem Referenzflugzeug auf dem Stand der A350-Technologie verglichen. Die Einsparpotenziale werden detailliert dargestellt, da bei einigen Technologien die gegenseitigen Wechselwirkungen entscheidend für das Ausschöpfen aller Möglichkeiten sind. Die Autoren gehen davon aus, dass das physikalisch und technisch fundierte Potenzial für Energieeinsparungen weit über *50 %* liegt. Selbst unter Berücksichtigung zusätzlicher Unsicherheitsmargen der Technologieannahmen, belaufen sich die Einsparungen trotz allem auf mehr als *40 %*.

Gestützt auf die vorgestellten Ergebnisse betonen die Autoren die dringende Notwendigkeit, gezielte Maßnahmen zur umfassenden und koordinierten Förderung der identifizierten Technologien zu verstärken. Nur durch solche Initiativen wird es möglich sein, die nötigen Technologien so weit zu entwickeln, dass sie bereits vor 2050 in zukünftige Produkte integriert werden können. Aus Sicht der Autoren stellt die Steigerung der Effizienz von Flugzeugen für das Erreichen der Klimaziele und für ein nachhaltiges Wachstum des Luftverkehrssektors den entscheidenden Faktor dar.

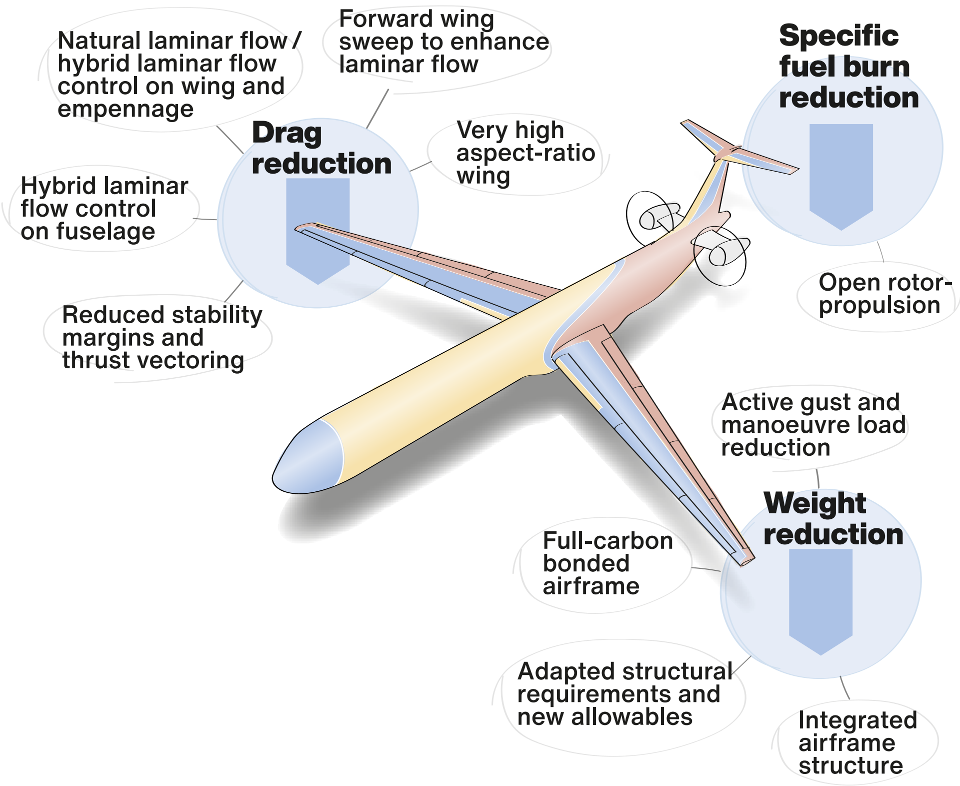

Abbildung 1: Wichtige Bausteine auf dem Weg zum energieeffizienten Flugzeug der Zukunft

L’avion du futur, économe en énergie: une perspective à long terme

Résumé

Dans le but de réduire considérablement l’empreinte carbone de l’aviation, voire d’atteindre un système à zéro émission nette d’ici à 2050, les parties prenantes de ce secteur sont confrontées à d’énormes défis. S’il est clair que ces objectifs ne peuvent être atteints que par l’utilisation de sources d’énergie renouvelables et durables telles que les carburants durables d’aviation (SAF) et l’hydrogène vert, leur disponibilité sera limitée et le coût du carburant associé à cette transition énergétique augmentera considérablement. Les défis découlent des investissements nécessaires pour développer les capacités de production d’énergie renouvelable, les infrastructures et la logistique, ainsi que des coûts récurrents plus élevés en raison de l’augmentation des coûts de production de SAF et d’hydrogène. Par conséquent, il est essentiel de prendre des mesures ciblées pour améliorer considérablement l’efficacité énergétique du système de transport aérien, en s’attaquant à la fois aux opérations de transport et à la conception des avions.

Dans cet article, les auteurs se concentrent sur ce dernier point, en examinant dans quelle mesure l’efficacité des avions peut être encore améliorée pour soutenir ces objectifs. À cette fin, diverses options technologiques sont abordées selon une approche équilibrée, en tenant compte à la fois de leur potentiel et des défis associés à l’amélioration significative de l’efficacité énergétique. Sur la base de nos conclusions, nous décrivons une voie à suivre pour parvenir à une réduction de *50 %* ou plus de la consommation d’énergie des avions du futur.

Dans le vaste domaine des technologies aéronautiques, nous mettons en évidence celles qui promettent les plus grandes économies potentielles en matière d’aérodynamique, de structures de cellules, de contrôle des avions et de systèmes de propulsion, permettant

également de dériver et d'évaluer des configurations d'avions prometteuses. Ceci est complété par l'identification des principaux catalyseurs, à savoir l'optimisation multidisciplinaire, les changements dans la certification des aéronefs et une révision des contraintes opérationnelles.

Les auteurs identifient les technologies clés suivantes comme des candidats à une intégration viable dans les futures classes de grands avions de transport bien avant 2050:

L'efficacité aérodynamique doit être améliorée par une approche équilibrée, combinant la réduction de la traînée visqueuse et la réduction de la traînée induite. Les concepts de techniques de réduction de la traînée visqueuse par le contrôle de l'écoulement laminaire sont bien compris, mais seulement partiellement démontrés à des niveaux suffisants de maturité technologique. Ils fourniront le meilleur effet de levier pour la réduction de la traînée visqueuse s'ils sont appliqués sur toutes les surfaces aérodynamiques, y compris idéalement le fuselage, pour lequel des solutions matures font encore défaut. Cependant, pour tirer pleinement parti du potentiel, l'exploitation nécessitera des avancées et des modifications de la conception de l'aile, des dispositifs hypersustentateurs conformes et du système d'actionnement et de contrôle. Ce dernier point en particulier ira de pair avec l'augmentation de l'envergure des avions du futur pour réduire davantage la traînée induite. Cela nécessitera des concepts structurels avancés, utilisant pleinement le potentiel des structures en polymère renforcé de fibres de carbone (PRFC), et des commandes de vol avancées permettant un contrôle actif de la charge. Cependant, les contraintes imposées par les normes d'infrastructure actuelles dans les aéroports empêchent la pleine exploitation d'avions avec des envergures nettement plus élevées que celles actuellement utilisées. Cela peut être surmonté par l'adaptation des normes aéroportuaires ou par l'intégration de nouveaux moyens techniques comme les extrémités d'ailes pliables dans les avions du futur.

Les **structures de la cellule** seront des éléments clés pour obtenir de nouvelles réductions de poids significatives, mais aussi des capacités fonctionnelles non atteintes avec les conceptions classiques. Pour cela, les auteurs considèrent qu'il est essentiel d'utiliser pleinement les capacités et les caractéristiques des matériaux en PRFC d'une manière parfaitement intégrée et cohérente. En raison des caractéristiques particulières des structures à base de fibres de carbone, certaines exigences de conception essentielles qui ont été introduites pour permettre des conceptions à sécurité intégrée dans les structures métalliques ne sont plus valables. Si des exigences de conception appropriées étaient adaptées aux propriétés physiques et aux caractéristiques du matériau et de la conception structurelle, des réductions de poids significatives et des fonctionnalités sur mesure seraient possibles, par exemple, dans le contrôle des charges structurelles et du flottement.

Combiné à des **technologies de systèmes avancées**, le **contrôle actif** de l'avion sera le principal facteur permettant d'obtenir des fonctionnalités telles que l'atténuation active des charges de rafale, des charges de manœuvre et même le contrôle du flottement, afin de réduire considérablement le poids de l'avion et de permettre la réalisation d'ailes avec des rapports d'aspect extrêmement élevés. En outre, cela peut contribuer à permettre des synergies nouvelles ou renforcées dans l'utilisation de l'énergie à bord de l'avion. Si l'on considère l'hydrogène comme une option prometteuse de carburant durable pour l'aviation, une série de changements seront nécessaires du côté des systèmes, notamment des réservoirs intégrés au fuselage et isolés, des systèmes de manipulation et de sécurité de l'hydrogène et de gestion thermique et hydrique. Cela permettra également de tirer parti de synergies supplémentaires, notamment avec de nouveaux concepts de gestion thermique utilisant l'hydrogène comme liquide de refroidissement et, avec l'eau, intégrés dans des architectures hybrides comprenant des piles à combustible et des turbines à gaz.

Des approches plus synergiques permettront également d'améliorer l'efficacité dans le domaine de **l'intégration de la propulsion**. Les nouveaux concepts de moteurs à très haut taux de dilution ou de soufflantes non carénées bénéficieront de l'intégration lorsque le couplage aérodynamique plus fort de l'aérodynamique de la cellule avec le flux de propulsion devra être délibérément contrôlé. Une technologie potentielle dans ce domaine est l'ingestion de couche limite (BLI), qui pourrait aider à réduire les effets néfastes de la traînée visqueuse sur le fuselage pour améliorer l'efficacité propulsive globale. L'utilisation d'eau de traitement pour les avions à hydrogène permet de réduire considérablement les émissions de NO_x et d'améliorer l'efficacité du moteur central.

L'intégration des différentes technologies dans une configuration d'avion spécifique montrera éventuellement le potentiel intégré, car les synergies peuvent être plus ou moins utilisées et les pénalités d'intégration peuvent être plus importantes dans certaines combinaisons que dans d'autres. Nous soulignons également que les exigences de haut niveau en matière d'aéronefs, les divers concepts d'exploitation avec une vitesse et une altitude de croisière modifiées, ainsi que les nouveaux concepts de routage, peuvent avoir des impacts significatifs sur les performances globales des avions et doivent être soigneusement examinés et probablement adaptés aux réseaux et opérations de transport du futur. Bien que les configurations d'avions radicalement modifiées présentent certains avantages spécifiques, les auteurs considèrent toujours qu'une configuration avancée de type fuselage intégré est prometteuse pour obtenir des réductions maximales de la consommation d'énergie.

Afin de quantifier le potentiel identifié, une combinaison exemplaire, mais très prometteuse de technologies est fournie pour une future configuration à courte et moyenne portée (SMR) et comparée à un avion de référence avec un niveau de technologie A350. Le potentiel d'économie est présenté en détail, étant donné que les interactions mutuelles sont essentielles pour que certaines technologies puissent déployer leur potentiel. Les auteurs prédisent un potentiel physiquement et techniquement solide pour obtenir des économies d'énergie bien supérieures à *50 %*. Même en tenant compte des marges d'incertitude supplémentaires utilisées pour couvrir les incertitudes actuelles dans les hypothèses technologiques, ces économies s'élèvent à plus de *40 %*.

Sur la base des résultats présentés dans l'article, les auteurs soulignent le besoin urgent de renforcer les mesures ciblées pour promouvoir les technologies identifiées de manière globale et coordonnée. Seules de telles mesures faciliteront la maturité technologique prête à être intégrée dans les produits bien avant 2050. L'amélioration de l'efficacité des avions est considérée comme un facteur clé pour atteindre les objectifs climatiques et permettre une croissance durable dans le secteur de l'aviation.

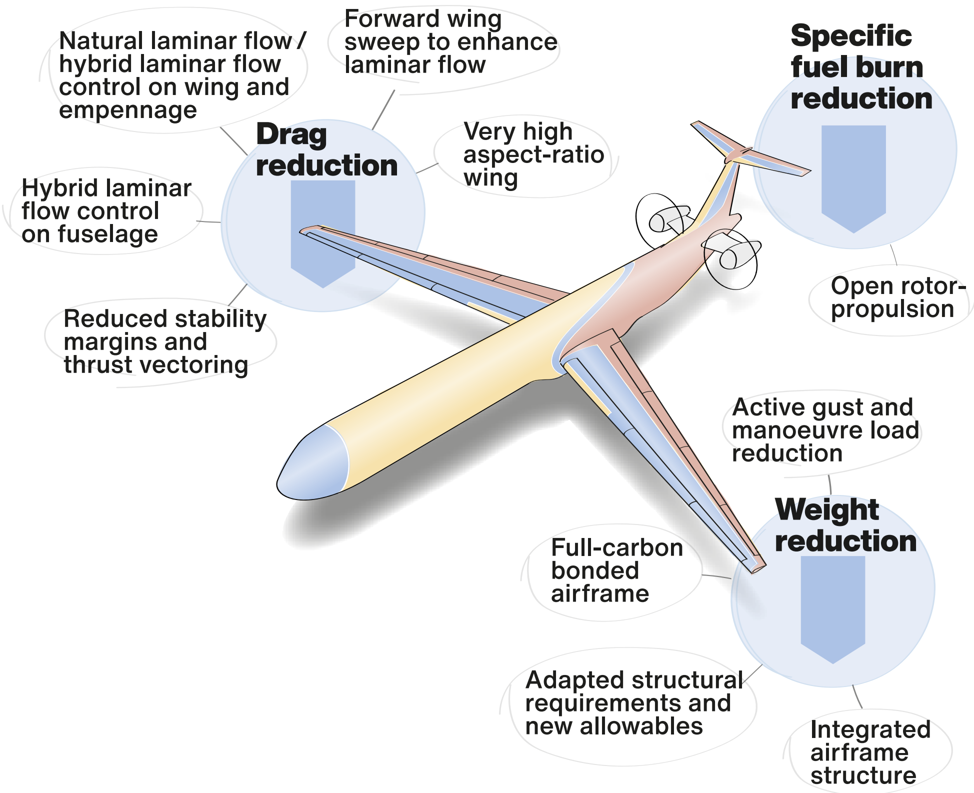

Figure 1: Éléments clés pour que l'avion du futur soit économe en énergie

1. Introduction: Energy Efficient Technologies for Sustainable Future Aircraft

For today's societies, standards of living and the availability of mobility are intrinsically linked. In addition to these societal and economic interdependencies, accelerating human-induced climate change has to be rigorously addressed, with greenhouse gas emissions to be drastically reduced if we are to at least limit climate change. This is well addressed in the 17 Sustainable Development Goals (SDGs) adopted by all United Nations (UN) member states in 2015, where "sustainability" is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" *[UN Brundtland Commission, 1987]*. The interdependencies for mobility are well reflected by SDGs 8 (Decent Work and Economic Growth), 9 (Industry Innovation and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action). A sustainable – i.e. highly efficient and climate friendly – mobility system is therefore an absolute necessity in order to protect the world's climate and at the same time achieve and/or maintain a high standard of living. For distances above *1500 km*, air transport is the only option for passengers and time-sensitive payloads. In general, compared to alternative systems such as rail and road transport, air transport requires minimal infrastructure, with local airports only at the start and end of travel, resulting in very little infrastructure on the ground. This is in stark contrast to the large investments and impacts required by ground-based transport systems for railways, roads, bridges, tunnels, etc. along the entire route.

In terms of climate impact, aviation contributes approximately *2.5%* to global anthropogenic emissions through the emission of carbon dioxide (CO_2), nitrogen oxides (NO_x), soot and noise, and furthermore by the formation of condensation trails (contrails). About *7%* of aviation's CO_2 emissions are produced by regional aircraft, *51%* by narrow-body aircraft of the Airbus A320 / Boeing 737 type and *42%* by wide-body aircraft of the Airbus A350 / Boeing 787 type *[ICCT Report 2019]*. Future air traffic growth scenarios roughly predict a doubling of global air traffic every 15 years, leading to a substantial increase in environmental impact in the absence of countermeasures. The overall goal for civil aviation must therefore be to develop a sustainable aviation system, comprising aircraft with significantly reduced or even close to zero climate impact. This document focuses on possible technological means to reduce the direct emissions produced by a particular aircraft when operating in the transport system, with the emphasis on large transport aircraft (short-, medium- and long-haul aircraft), the main contributors to the climate impact of civil aviation.

Emissions from today's air transport are directly linked to energy consumption, i.e. the fuel burned by the aircraft fleet operating in today's system. Reducing engine fuel consumption and increasing aircraft efficiency are thus key elements in reducing these emissions. Over the last few decades, impressive efficiency improvements have been made in each new generation of aircraft – both on the airframe and the engine side. However, these reductions in aircraft fuel burn have been outpaced by the overall growth in global air traffic, resulting in ever-increasing overall emissions. Therefore, if the predicted traffic growth continues, simply maintaining the current rate of technological efficiency improvement will be far from sufficient to achieve the ambitious emission-reduction targets of sustainable aviation. Achieving a sustainable air transport system will require significant acceleration in developments, including step changes in technologies to reduce fuel burn and increase efficiency. Broadly speaking, two technical areas will offer the greatest leverage for direct emissions reduction at the aircraft level:

- **improving engine technologies**, i.e. cutting emissions and reducing engine-specific energy consumption;

- **improving airframe technologies** – i.e. reducing aircraft drag and weight – to directly lessen the amount of energy required for flying.

The most direct way to reduce aircraft emissions is to tackle the problem at the source, i.e. the engine. Since the advent of jet engines, incredible progress has been made to reduce specific fuel consumption – not least through ever-increasing bypass ratios. Further gains in engine efficiency are possible by continuing along this "classic" path, but the corresponding technologies will reach asymptotic saturation.

Another promising option for reducing climate impact is to switch from today's kerosene to synthetic fuel (sustainable aviation fuel, or SAF), requiring only a relatively simple adaptation of today's engines. A prerequisite for substantial reduction of CO_2 emissions is a cyclic, climate-compatible production of SAF based on renewable "green" energy and "carbon capture" technologies that offset the CO_2 from burning SAF by removing CO_2 from the atmosphere for SAF production. Sustainable, climate-compatible SAF production requires a highly energy-intensive power-to-liquid (PtL) process based on carbon capture, electrolysis, and Fischer–Tropsch synthesis.

A further feasible option is the direct combustion of hydrogen (H_2) using adapted jet engines and associated aircraft systems. Hydrogen storage and handling technologies are highly complex and, particularly for long-range transport aircraft, the weight and size of H_2 tanks are detrimental to energy efficiency. H_2-based propulsion systems will be completely CO_2-free, but will still produce NO_x and water, with water vapour emissions potentially contributing to climate change through increased contrail formation.

Regarding other alternatives for aircraft power generation, from a technical point of view it is generally agreed that electricity-based systems (using batteries, solar panels or H_2 fuel cells) for powering large aircraft face extreme challenges in terms of energy and power density.

Due to the limited possibilities of technical alternatives, propulsion systems based on combustion engines will represent the most feasible option technically in the coming decades, with SAF and/or H_2 as the preferred energy carriers to reduce climate impact. This will have two main consequences: on the one hand, due to combustion processes, emissions from air transport will not be completely avoided; on the other hand, the high cost of producing SAF and H_2 will lead to substantially higher fuel prices as compared to today's kerosene. A future sustainable air transport system will thus face two very serious challenges: to reduce the remaining emissions to a technically feasible minimum, and to ensure a transport system that is still affordable for the majority of citizens and economically viable for commercial operators. Failure to meet the first challenge will lead to further climate change and as such will be unacceptable to society, and failure to meet the second challenge will lead to the eventual loss of air transport mobility, with all the negative consequences for future living standards and economic growth.

For these ecological, economic and societal reasons it is of paramount importance to drastically reduce the energy consumption of future narrow- and wide-body aircraft. Therefore, this document will focus on the second technical area, the improvement of airframe technologies. The renowned authors of the document showcase that there is a physically and technically sound potential to achieve up to *50%* improvement compared to today's state of the art by directly reducing the energy required for flight, i.e. mainly by minimizing aircraft drag and weight. With respect to the engine, technologies for increased external kinetic propulsive efficiency will be addressed, while internal thermodynamic efficiency will only briefly be touched upon. Where the airframe is affected, for example by the integration of novel propulsion systems or new H_2-fuel systems (especially the tank), specific power-plant aspects will also be considered.

The technologies and measures suitable for improving efficiency will be considered within the next two main chapters. After the current introductory chapter, the **second chapter** will identify individual technical improvement opportunities. Overall aircraft aspects such as new architecture and configurations, as well as design tools and development aspects like certification, will be addressed in the **third chapter**. The **fourth chapter** will briefly touch upon other important factors of the general air transport system, such as overall performance of the transport system, aspects of air traffic control and operations such as formation flight and noise, and overarching life cycle aspects.

The technical subchapters of the document are structured in a "thesis – antithesis – synthesis" manner. First, the physical and technological potentials are highlighted, followed by an outline of the challenges for realization in an aircraft. Then, in the synthesis part, for those technologies and measures that are considered to have a realistic chance of being implemented in future generations of commercial airliners, the necessary steps to achieve the required maturity level are addressed. In aviation, this is crucial because of the very high level of safety required, where new technologies and methods must be thoroughly assessed and validated before application.

Essentially, most of the considered technological improvements are not new in aeronautics – there are not many real “white spots” left after decades of research and technology development activities. However, in the past, many technologies have either been rejected during the assessment phase of a new development program or have only been partially used, e.g. for load alleviation. The engineering and manufacturing know-how and certification rules in place at the time did not allow full technological exploitation, or commercial reasons and market requirements were not favourable to the technologies' introduction. In contrast, today, with critical environmental challenges clearly in mind, the weighting of the evaluation criteria has changed in terms of cost effectiveness, and further improvements from evolving technologies (in the recent past and in the future) have the potential to change the overall picture: while environmental aspects have always played a role in the evaluation process, they may now dominate. Thus, technologies that did not pass the selection process in the past may now be considered to help reach emission-reduction targets.

The research and development paths proposed in this document to achieve the envisaged drastic reductions in energy consumption represent a paradigm shift from the current incremental improvement to a step change approach. Therefore, a disruptive development process appears to be inescapable in order to master this necessary step change approach – in terms of technology maturation and selection, technology validation in a full-scale demonstrator program and even funding – and to change to a mode of taking (well assessed and mitigated) risks. Otherwise it will not be possible to achieve a *50%* improvement within the next two to three decades.

In this process, it is, however, mandatory to maintain or even improve the current level of safety, since any relaxation of current safety levels would be unacceptable due to potential fatal consequences. Thus, civil aviation faces an enormous future challenge: step changes in technologies are inevitably associated with uncertainties, but radical progress cannot be achieved without technologies beyond current knowledge. Strictly staying within the perimeters of current knowledge to avoid these uncertainties will result in a too-restrictive technological solution space, blocking any of the necessary radical improvements. Therefore, to advance towards technical solutions beyond current knowledge, the step change approach mentioned above has to be addressed rigorously, still keeping safety as an overarching requirement. In the third chapter a special subchapter is dedicated to outlining a sound perspective on sequentially using discrete development levels to enable this approach.

1. INTRODUCTION

2. Energy-Efficient Aircraft Technologies

This chapter delineates technological pathways for a drastic reduction of aircraft energy consumption by airframe technologies. Essentially, this addresses the reduction of aircraft drag and aircraft weight, i.e. the disciplines of aerodynamics and structures. However, these disciplines cannot be optimized individually due to their strong interdependencies, which have to be analysed and mitigated. Here, any active means to enable improved aerodynamics, to reduce loads for lighter structures or to enhance flight control requires aircraft systems that are able to provide the necessary actuation capabilities. For the highest propulsive efficiency, the interaction between the airframe and the propulsors has to be rigorously addressed, either by minimizing any detrimental interference or by identifying and subsequently exploiting possible synergistic effects. In the subchapters to follow, these technological aspects will be highlighted in a "thesis – antithesis – synthesis" manner, where first the ultimate potential will be outlined, then the challenges for leveraging this potential, and then ways will be sketched for how to face these challenges.

2.1 Drag Reduction

For cruise flight, the required power of the propulsion system has to balance the flow losses from aerodynamic forces that are parallel to the direction of flight. These forces are called aerodynamic drag. Aerodynamic drag mainly results from the effects of viscous and turbulent momentum transport within the surrounding air flow, from compressible wave effects at flight speeds close to the speed of sound, and from energy losses due to the creation of lift for compensating for the aircraft's weight. Thus, the main components of aerodynamic drag are viscous drag, wave drag and lift-induced wake vortex drag (or, in short, "induced drag"). Note that these three fundamental drag sources also include the usually adverse effects of aerodynamic interference on the major airframe components such as wing, fuselage, empennage and engine nacelles, as well as other miscellaneous drag contributions. The relatively smaller portions of the overall drag breakdown, wave drag and interference drag, can be well minimized by available means of geometry optimization. For the highest aerodynamic efficiency, i.e. the highest ratio of lift to drag, the ratio of induced drag to total drag should be about *40%*. If we subtract the induced drag, the miscellaneous drag and the wave drag from the total drag, we obtain a share of around *52%* for the viscous drag. This share can be directly influenced by viscous drag reduction measures.

2.1.1 Reduction of Viscous Drag

Introduction

The flow of the boundary layer close to the surface of existing commercial aircraft is almost entirely turbulent. The shear force of the fluid at the surface generates the skin friction drag of the aircraft, while the adverse effect that the boundary layer has on the pressure at the surface generates additional drag known as pressure drag. Hence, the viscous drag of an aircraft comprises skin friction drag and pressure drag. While means of active drag reduction for turbulent boundary layers, e.g. oscillating surfaces or dynamically morphing surfaces, appear unfeasible for the coming two to three decades, the most promising passive means are surfaces with small ribs aligned in the flow direction, called riblets. The theoretical potentials of reducing the viscous drag of turbulent boundary layers with riblets are limited, somewhat below *10%* of the viscous drag. Application of riblets has been developed to high technology readiness. Both adhesive films and tailored paints with the riblet structure are now available. However, such surface treatments cannot be used in areas with rapid flow changes, typically present over large portions of the wing and tail surfaces. Therefore, current applications integrate the riblet function on parts of the fuselage surface and on parts of the wing. The technology is presently close to introduction by major airlines. The only promising approach to achieve more drastic reductions of viscous drag is the comprehensive **laminarization of aircraft components**, as the viscous drag of a laminar boundary layer is one order of magnitude below the turbulent value.

Potential

The extent of a laminar boundary layer is generally determined by three factors: Reynolds number, pressure distribution over the surface, and active control of the surface flow condition. The aerodynamic and structural technologies for wings with natural laminar flow (NLF) without active control have been developed up to *TRL 5–6* for commercial aircraft of small and medium size. The potential for overall drag reduction for laminar wings during final climb segments and cruise depends on the engine integration and aircraft mission. It may be estimated at *12–17%* at the aircraft level, assuming successful application on upper and lower wing surfaces. Comprehensive drag reduction for wings of large aircraft, for highly swept tailplanes and for the fuselage makes application of laminar flow control (LFC) by suction necessary. The overall drag reduction potential for a laminar fuselage with LFC is about *10–14%*, and rather low suction rates are needed for controlling the laminar boundary layer.

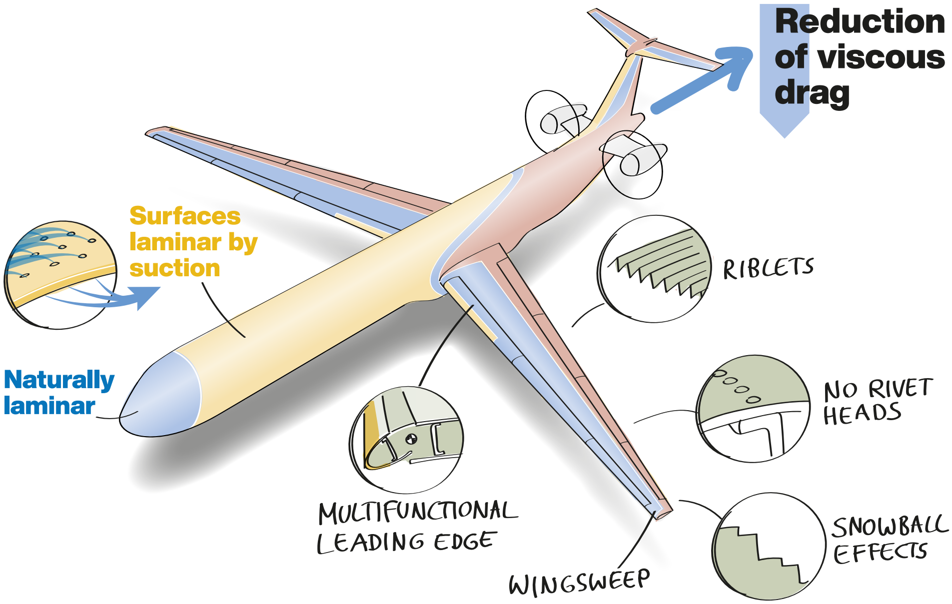

Figure 2: Laminar flow technology to reduce the viscous drag

Preliminary aircraft design studies indicate that the theoretical overall, long-term potential of viscous drag reduction on overall aircraft drag is about *40–50%* depending on aircraft mission, if the snowball effects on overall aircraft level, e.g. new design of wing planform and resizing of aircraft, are taken into account. The drag reduction translates directly into reductions of fuel consumption, aircraft exhaust emissions into the atmosphere and consumption of primary energy by aviation in general. The huge technology potential for aircraft energy consumption makes laminarization a strong enabler of competitive future commercial aircraft.

Challenges

The present status of the risks of laminar flow technology (NLF and LFC) puts a significant uncertainty margin on the viable reductions. While resizing of aircraft due to viscous drag reduction will result in an aircraft empty-weight reduction of *4–8%*, that saving could be partially offset by the additional weight of the LFC system as well as by the energy losses associated with the powered suction system. Further, the feasible amount of flow laminarity along the span of a fully integrated wing with movables is uncertain. We presently estimate the uncertainty at *20%* of the overall benefit stated above.

Laminarization of aircraft bears significant complexity because of the strong and multiple interactions between flow physics, compliant structures and the suction systems design. This insight is a strong driver to fully exploit the benefits of NLF in the first applications to large commercial aircraft. Compliant suction shells with acceptable cost and weight are key technologies for comprehensive drag reduction with laminarization using active flow control. Such suction shells shall carry structural loads and hence allow a stressed design. Segmentation of the shells, e.g. along the span of a wing, must not lead to premature transition. The suction shells must also be resistant to sand erosion and de-icing fluids. While significant research on hybrid laminar flow control (HLFC) for controlling crossflow instability at the nose region of swept wings has led to *TRL 3–4* in Europe, it appears that a fully compliant, multifunctional leading-edge concept is not available. The compliant leading edge must offer sufficient design space for achieving high lift; it must maintain laminar flow along almost the complete wingspan on upper and lower wing surfaces; it must comprise an insect-shielding function or alternatively a cleaning function during flight; and it must be safe in case of bird strike. On the other hand, there is practically no research on LFC for fuselages, in spite of the fact that low suction rates theoretically suffice to keep a large portion of the fuselage surface laminar. Hence, no compliant structural concept for the laminar fuselage is known.

The requirements of acceptable cost and resilience during operation demand significant investment into industrialization of manufacturing concepts and introduction of new concepts for distributed systems for wings, fuselages and the other aircraft components. This especially holds for HLFC. The high level of quality assurance during production of laminar aircraft components, the need to monitor and maintain the high requirements for surface smoothness, and the function of LFC during aircraft lifetime will lead to significant additional costs in maintenance, repair and overhaul (MRO). These effects reduce the economic value of the technology for the manufacturers and for the airlines.

The lack of fundamental knowledge of compliant structures for LFC, the lack of industrial experience in resilient system design and the lack of knowledge on cost-efficient production lead to significant technology risk. This risk can only be reduced by strategic long-term research action.

Synthesis

The imperative to minimize the environmental impact of commercial aviation in the near future will drive the adoption of laminar flow technology. Several factors will contribute to this disruptive shift.

Firstly, **fuel costs** are projected to increase significantly, potentially by a factor of *2–5* compared to current kerosene prices. This escalation will be influenced by the availability and cost of hydrogen (H_2) and sustainable aviation fuels (SAFs) over time, as well as the yet-uncertain feasibility of using hydrogen as the primary onboard energy source.

Secondly, **fuel consumption** in commercial aircraft can be effectively reduced by decreasing flight speeds. This reduction leads to lighter aircraft, diminished wave drag and less stringent requirements for high-lift systems.

Thirdly, it is well established that the **radiative forcing** of the atmosphere by aircraft engine exhaust can be substantially decreased by flying at lower altitudes. However, the atmospheric sensitivity to radiative forcing varies significantly by geographic location. Therefore, to mitigate this adverse impact, there is a need to reduce flight speeds while maintaining aerodynamic designs that provide high performance across a relatively broad range of cruise Mach numbers and lift coefficients.

The expected change in high-lift requirements will make it possible to use non-slotted, hinged droop noses instead of slats or Kruger flaps, thereby opening the door to achieving laminar flow on upper and lower wing surfaces. Therefore, the hinged droop nose can assume the role of a multifunctional leading edge, to be used for protection against bird strikes and aircraft icing, for control of wing torsion and for high lift of NLF wings. Further, it has to provide the HLFC function, in the case of HLFC wings. The new leading edge will necessitate new technologies for sealing and for limiting the geometric distortions imposed by the junction to the wing box, so that laminar flow can be maintained. Full exploitation of this concept for NLF on the wing appears very promising for reduced Mach numbers and hence reduced wing sweep, as described above. Outside of the useful NLF design space, it appears that industrialized suction surface sheets combined with functionalized sandwich cores and bonding to the inner shell are not yet available. Tailored suction orifices, additive manufacturing and structural bonding could be critical technology ingredients that need to be developed to the production scale of droop noses. We also note the great potential offered by a multifunctional droop nose, to simplify the MRO processes. In addition, a cleaning function must be provided for use in flight after take-off and initial climb. Such a cleaning function could be assumed by suitable surface coatings or, alternatively, by miniaturized robots that can adapt to the changing geometry of the wing nose from root to tip.

Exploitation of the laminar flow potential of wings and tailplanes will furthermore require fully three-dimensional aerodynamic design capability, including reliable transition prediction that is coupled to structural analysis in order to achieve multi-disciplinary optimization. We also note that the laminar wing surface should be free of rivet heads, as the related material discontinuities lead to rather high degradation rates for the surface finish.

These considerations set the stage for successive introduction of viscous drag reduction technologies on future commercial aircraft as follows:

- The viscous drag of the turbulent wing and fuselage can be reduced by introducing **riblets** to the appropriate surface portions of existing aircraft within 5 years. This will reduce overall aircraft drag by *1.5–2%*. The most important step in the exploitation of laminar flow technology for commercial aircraft will be the introduction of NLF for the aircraft wing. This step will build on the experience gained from the EU-BLADE technology demonstrator. We expect that it will be possible to advance the multifunctional leading-edge approach described above as an enabler of NLF on the wing's upper and lower surfaces to *TRL 6* by the year 2035. This will lead to an overall drag reduction of around *16–21%* (including snowball effects on overall aircraft design, OAD) for short-range and mid-range aircraft at current cruise speeds.

- The introduction of comprehensive **laminar flow technology** for wing and empennage of large, long-range aircraft will take significantly longer, as the AFC (active flow control) function must most likely be included in the multifunctional leading edge. We think that this goal can be reached by the year 2040.

The snowball effects of laminarization on the OAD level are large, as indicated by the drag reduction percentages given above. Therefore, we note here that it will not be possible to design a competitive aircraft with a laminar wing based on an overall aircraft design that was previously defined for a turbulent wing.

We recommend overcoming the present lack of knowledge on laminar flow fuselages through two main steps. In the first step, the fundamentals of aerodynamic design and compliant shell structures shall be developed to about *TRL 3*, which is needed to assess the feasibility of fuselages with about *50%* laminar flow. The initial research should address the questions of whether suction surfaces exist that can maintain laminar flow over infinitely long distances, whether there exist optimum designs for fuselage geometry and boundary layer augmentation by suction and whether there exist lightweight double-shell concepts that can generate the aerodynamic suction function, carry the fuselage loads and satisfy basic MRO constraints. The feasibility of manufacturing such structures must be also analysed. A particular challenge appears to be the integration of passenger doors and emergency exits. A positive outcome of the first step would then justify the large investment of the second step, through which viability of a laminar fuselage is demonstrated. We estimate that it will take about *15–20 years* of coordinated research to achieve *TRL 6* for the laminar fuselage.

2.1.2 Reduction of Induced Drag

Introduction

Lift-induced drag results from energy losses due to the creation of lift for compensating for the aircraft's weight. These losses are mainly caused by the fact that finite-span lifting wings generate longitudinal vortices in their wake. As the main components of aerodynamic drag during cruise are viscous drag and lift-induced wake vortex drag, the aircraft design must aim at minimizing both the viscous drag and the induced drag. For induced drag, there are two main levers for reduction: driving wing design towards an **optimal elliptic load distribution** along the wingspan, and **increasing the wingspan** as much as possible.

Potential

The increase of wingspan represents a very effective option, since induced drag depends on the reciprocal square of the wingspan, so doubling the wingspan reduces induced drag by a factor of four. The increase in wingspan should, however, not lead to an increase of "wetted" surface, since this would increase viscous drag. Thus, to keep the wing area constant when increasing wingspan, wing mean chord length has to be reduced accordingly. The ratio between wingspan and mean chord length is called aspect ratio (AR; also expressed as ratio of wingspan squared to wing area), and thus an efficient wing with high span to reduce induced drag leads to a high aspect-ratio wing (HARW), i.e. to a very slender wing with high span. The potential of high aspect ratio wings for induced drag reduction is well established in aeronautical science, and pronounced high AR wings are typically seen for high-performance gliders with AR of about *25*, and in the extreme even to *50*. Due to the inverse quadratic span dependence, an increase of span by a factor of *1.5* reduces induced drag by somewhat more than a factor of two. If the wing area increases linearly with span, AR also increases by *1.5*, while keeping the wing area constant leads to a doubling of AR. Today's modern civil transport aircraft feature AR on the order of *10*, so halving induced drag with a constant wing area will require AR of about *20*.

Challenges

The increase in aspect ratio for large transport aircraft poses several severe challenges, and there are good reasons for today's aspect ratios with values around *10*. The major two challenges for high aspect-ratio wings are achieving sufficient stiffness of the wing structure and preventing flutter at high dynamic pressures, and airport regulations may restrict the maximum admissible span. The high span will lead to substantial wing bending and torsion moments, and due to the thinness of high aspect ratio wings, materials with special stiffness and strength properties are required. For civil transport aircraft flying at transonic speeds, the challenge of withstanding bending and torsion moments is aggravated by the necessary wing sweep. Furthermore, due to the thinness of high aspect ratio wings, even with very advanced materials, such wings will exhibit substantial elastic behaviour. Thus, an interaction between the elastic wing structure and the aerodynamic forces becomes inevitable, and unwanted reversal of control effectiveness by movables as well as wing flutter pose a permanent challenge.

Besides stiffness and flutter, additional challenges are associated with high aspect ratio wings: The high span may lead to compatibility concerns with respect to the limitations of airport infrastructures, and the relatively small wing volume may restrict the retractability of the landing gear at the wing root. Furthermore, the integration of high-lift systems with flaps and slats becomes a substantial challenge due to volume restrictions, and for long-range kerosene-based aircraft the amount of storable fuel may also be limited.

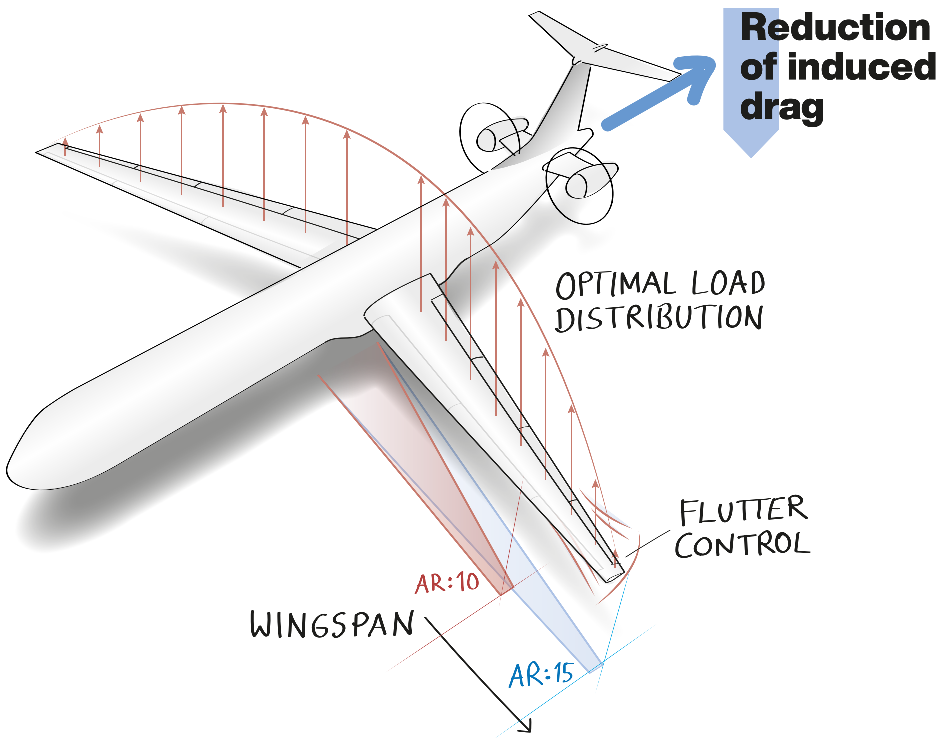

Figure 3: Reduction of the lift-induced drag through a high aspect-ratio wing concept

Synthesis

The introduction of the cantilever wing by Hugo Junkers in 1915 to replace wire-braced designs was a major breakthrough for aircraft structures. Advanced materials like carbon fibre reinforced plastics (CFRP) bear the potential to realize cantilever high aspect ratio wings, and such materials are already in use today. However, the unidirectional properties of such materials must be fully mastered with new construction principles (see *Chapter 2.2* for more details). This may in turn require unusual concepts for incorporation of control surfaces, high-lift systems, tanks and landing gear. Subsequently, today's certification requirements, which are mainly based on the behaviour of metallic materials, need to be adapted to CFRP properties.

Winglets are nowadays a common device on large transport aircraft to reduce induced drag while meeting wing-span limitations. Further advancements in materials and autonomous electric actuators offer the potential to adapt winglets to different flight conditions, and especially in combination with local laminar flow, the efficiency of these devices may be further enhanced. Another means to alleviate the restrictions of high-span wings in airport ground handling is represented by **foldable wing tips**, which are being investigated now. Here again, when consequently exploiting the unidirectional properties of CFRP materials, an efficient load transfer from the joints into the wing structure may, however, require novel construction principles different to today's mainly metallic-based designs.

Passive and active load alleviation to alleviate gust and manoeuvre loads is a well-known technology to reduce wing-root bending moment. However, in order to realize cantilever wings with aspect ratios on the order of *15* or more without severe weight penalties, today's state of the art is not sufficient, and **load-alleviation technologies** have to be consequently pushed forward in research and development. Therefore, the interplay of passive and active load-alleviation concepts must be fully understood, especially when using CFRP materials. Further, the availability of fast actuators of movables is key for effective load alleviation. Also, combination with foldable wing tips may be envisaged by controlling the bending moment at the folding joints to reduce overall wing-bending moment. Technical concepts from passive and/or active load alleviation are similarly applicable for control of flutter and limiting cycle oscillations; therefore, research and development of load-alleviation technologies should always be performed in conjunction with flutter control (see *Chapter 2.3*).

As outlined above, cantilever wings are favourable for high speeds but require relatively heavy structures. Thus, today truss-braced and strut-braced wing concepts are being investigated, where the additional structural layout alleviates the load bearing for the main spar. The challenges for such concepts are represented by complicated structural load paths, aerodynamic penalties due to additional wetted surfaces and transonic interaction at the joints, as well as yet-unknown flutter phenomena to be considered in multi-disciplinary design optimization. Other concepts to reduce wing-bending moments incorporate more severe configurational changes, such as non-cylindrical fuselage shapes to create additional lift at the aircraft centreline for reduction of wing root-bending moments, or double fuselage concepts to achieve a more favourable spanwise mass distribution.

Concerning the incorporation of high-lift systems, two main pathways may be followed: either the wing surface, i.e. chord length, is increased such that the best compromise between aerodynamic wing loading and conventionally achievable high-lift performance is identified (note that induced drag depends on span and not on aspect ratio), or high-lift performance may be increased with future small and lightweight, more powerful actuators and/or with advanced suction / blowing flow control devices (cf. Chapter 2.5). Most probably, future technical solutions will eventually feature a combination of both approaches.

When a particular high aspect ratio wing does not accommodate the necessary fuel volume, a compromise between larger wing volume, i.e. aspect ratio reduction, and additional tanks in the fuselage or empennage has to be found. Then a careful balance must be established between higher wetted wing surface and increased wing root-bending moments due to additional mass along the aircraft centreline.

The typical means of landing-gear integration on swept transport aircraft wings is a Yehudi, where close to the wing root the trailing edge does not follow the sweep anymore but is drawn perpendicular to the aircraft centreline. For high aspect ratio wings additional extensions at the wing root may be necessary, either by increasing the wing root area or by locally extending the fuselage. This may in turn lead to substantial changes to the overall aircraft configuration.

These considerations set the stage for successive steps in reducing the induced drag for future commercial aircraft:

- The increase of the wing aspect ratio from *10–12.5* is possible by the year 2030, by application of a **lightweight-structure CFRP wing**. This increase will reduce the induced drag by *20%*, assuming that no change in the required wing area is applied. This will translate into drag reduction for the overall aircraft of *8%*.

- The increase of the wing aspect ratio to values around *15* will introduce significant complexity for cantilever wings. In that case, technologies for **load alleviation and**

flutter control must be applied in order to keep wing structural weight within reasonable bounds. As these technologies bear significant uncertainties because of the needed system technologies (see *Chapter 2.5*) and the required aircraft certification, this step could probably reach *TRL 6* around the year 2035, or even later. When the wing area is held constant, achievement of this step will reduce the induced drag by *34%*, translating into drag reduction for the overall aircraft of *14%*.

We recall that reduction of the induced drag alone does not lead to a balanced aircraft design, as it must be accompanied by a suitable reduction of the viscous drag.

2.2 Airframe Structures

Weight saving is a key enabler for low fuel burn and hence lower emissions. In recent decades, the weight of the airframe structure has been reduced significantly. Advanced materials and manufacturing technologies, welding and bonding have found their way into the latest generations of airliners.

Despite the successful introduction of carbon fibre composites, aluminium, steel and titanium alloys still have a share of roughly *50%* by weight. The airframe consists of a mix of metallic and composite structures, called hybrid design. Although new alloys and advanced manufacturing technologies may add some benefit, this mix of materials limits the potential for additional weight savings.

Substantial performance improvements can be achieved when almost exclusively using carbon composite materials. Changing gradually from aluminium alloy to composites during the most recent decades has been a careful, step-by-step process. There have been only minor drawbacks on this road – accompanied by much learning and a corresponding accumulation of experience. For composite structures, fatigue and aging are not critical factors; this has been proven since 1985 by over more than 500 million flight hours.

On this sound and solid basis, the potential of advanced composites can be raised to much higher levels in future aircraft structure design. Although composites dominate in the latest airliner generation, design and stress principles in a hybrid design are still metal (aluminium) based. Fatigue principles, corrosion protection schemes and riveting cause problems for the optimization of a composite structure. As a result, nowhere near all the potential improvements have been achieved in comparison to what this material offers. Also, a significant number of limitations related to principles from metallics are still present in the design of composite structures, since it was a new technology for some period.

This chapter will focus on a full composite airframe as the dominant material for future airliners.

The potential improvements will be leveraged along three directions:

- Primary structure weight savings due to **carbon airframe fully bonded**
- Primary structure weight savings due to a **requirements challenge**
- Airframe performance improvements due to weight savings through **function integration**

This is to be complemented by adapted certification rules.

It is of the utmost importance that the current level of safety is maintained and even increased. This must be ensured through the application of appropriate design and load factors as well as adapted requirements and certification rules.

Based on decades of experience with advanced composite materials in service, this document makes suggestions for potential weight savings on the order of *20%* of the operational weight empty (OWE) of a current metallic SMR aircraft. A *20%* advantage in OWE accounts for *12–13%* block fuel reduction of an SMR aircraft, not taking into account any snowball effects. Some can be realized for entry into service in 2035, others only after dedicated further research and technology development efforts. However, a detailed assessment of the aforementioned potential for specific applications in future aircraft is beyond the scope of this document.

2.2.1 Carbon Airframe Fully Bonded

Introduction

Despite the success of carbon fibres in modern aircraft like the A350, the potential of composite structures is not fully leveraged yet. In this subchapter, the possible weight savings are related to the primary load-bearing structure of the aircraft. For an SMR aircraft, this is around *35%* of the OWE (excluding landing gear). Current weight saving for the airframe's primary structure is at best *15–20%* compared to an aluminium design, although carbon composite materials have a density advantage of *40%*.

Aluminium structures are subject to fatigue and crack growth; the sizing of composites is based on no growth in impact damages.

Aluminium fatigue / corrosion principles depend on the knowledge of crack detection and crack propagation and a sufficient margin to ensure timely discovery before a crack becomes critical, i.e. before load-bearing capability is reduced to limit load (LL=max. load once in the lifetime). Fatigue may occur at typical in-service loads, i.e. loads less than LL. Consequently, to date the factor of safety has been set to *1.5*, which means *50%* margin above LL, called ultimate load UL. This factor of safety has been in use since the 1930s and does account for unknowns, like in the load and stress calculation, unidentified manufacturing defects, unpredicted operation conditions, etc. In addition, it does provide a margin to ensure timely detection of cracks before load-bearing capability is reduced to a critical level.

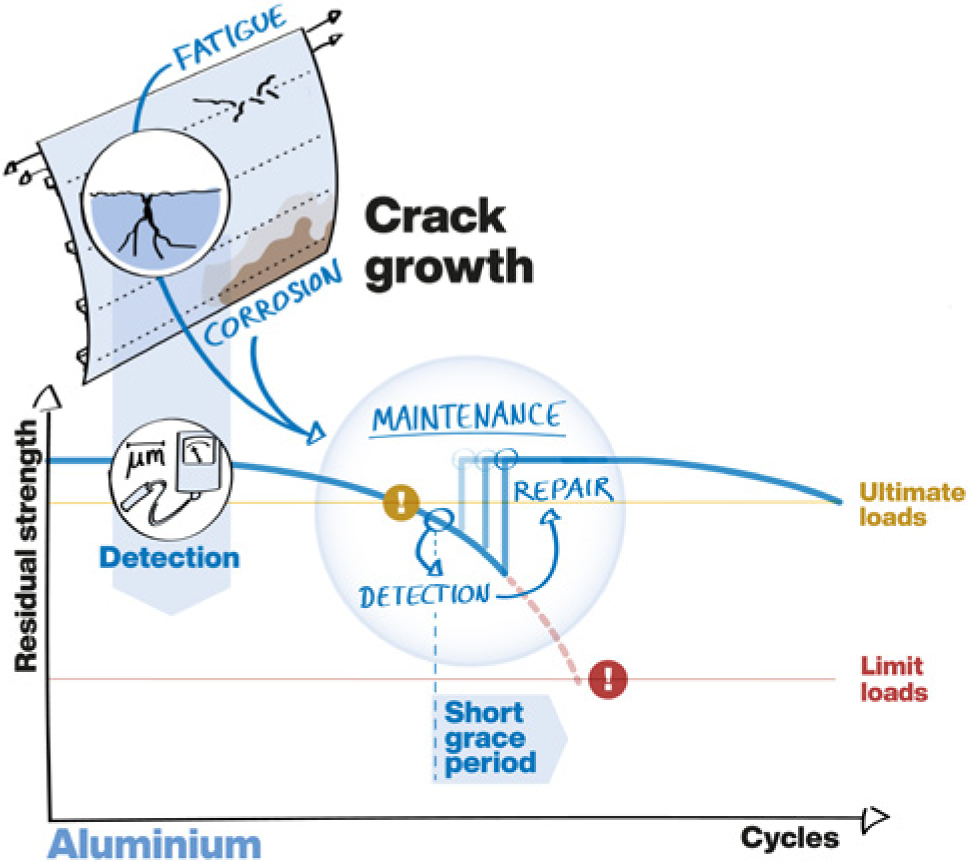

Figure 4: Damage tolerance behaviour of aluminium structures

From a safety perspective, aluminium structures require thorough, instrumented inspection and maintenance schemes, to discover cracks and corrosion well before load-bearing capability is reduced to LL and below. Timely repair / restoration of UL capability is mandatory.

In contrast to aluminium, **carbon fibre composites** (monolithic structures) do not suffer from any fatigue or corrosion effects. The challenge for composites is to cope with damages from impacts in aircraft operations. Depending on the force, an impact damage may be invisible, barely visible, potentially visible or obviously visible (cannot be overlooked at preflight check). For carbon composites, it has been demonstrated by certification test campaigns and in-service experience that a structure with a barely visible impact damage sustains UL. Only obviously visible impacts may reduce the load-bearing capability to less than LL. Every potentially visible impact damage sustains more than LL. For all defects smaller than the obviously visible, no growth has been demonstrated successfully for composite primary structures of CS / FAR 25–type aircraft. Nevertheless, the factor of safety is still *1.5*, as it is for aluminium structures.

Carbon composite structures are inspected visually, and safety-related damages (load-bearing capability less than LL) are detectable at preflight check. Smaller defects are uncritical because of no growth and may remain undetected; this does not impose any safety issue. (Note: From a regulatory perspective, restoration of UL capability is required; a detailed review of this is discussed in *Chapter 3.4*, on certification.)

Mainly because of this, monolithic carbon composites have proven to be robust; no in-service material failures have occurred since the introduction of the first primary structure in 1985.

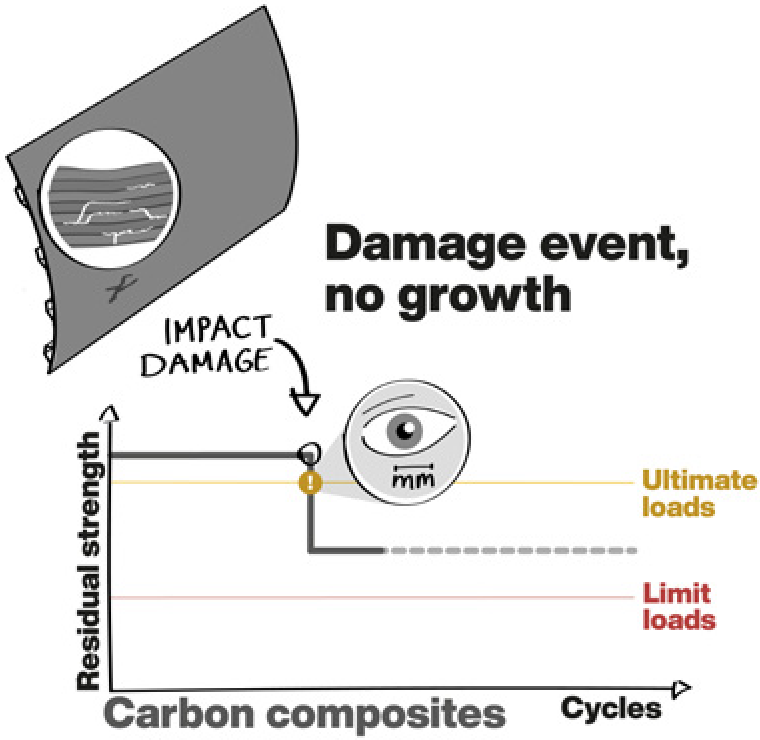

Figure 5: Damage tolerance of carbon composite structures

A hybrid, non-monolithic structure, containing elements with a mix of aluminium and composites, cannot benefit from the specific fatigue and corrosion advantages of composites. Even worse, thermal expansion mismatch and necessary corrosion measures (protection schemes and extended use of titanium) reduce performance and add weight and costs.

Potentials

Today, composites are subject to design and certification concepts derived from aluminium structures. A pure composite design has the potential for further weight saving. Also, the joining concept can be improved, reducing / eliminating riveting by bonding, if designs for bonding and mature processes are employed.

Carbon composites – as shown by experience with today's max. strain levels of around *4000 microstrain* – do not react to cracks, and damages do not grow. This advantageous behaviour shall be used at even higher strain levels. Today, this decisive advantage of no fatigue, no damage growth and no corrosion is not utilized, neither exploited in design nor recognized in certification concepts. Means of compliance are not yet fully adapted to composites, mainly because load-bearing elements are made from a mix of aluminium and composite. Instead, components and inserts made of steel or titanium should be used in areas of high load concentration and bolts.

As a consequence, in this document a paradigm change is proposed to fully employ the advantages of carbon composites, the **carbon airframe fully bonded (CAFB)**, complemented by a shift in joining technology and a design change from riveted to bonded.

A fully carbon-based primary structure may achieve weight saving of *40%*, more than twice the weight saving that has been achieved so far with a conventional hybrid structure, at much lower production and maintenance cost. Additional savings potential will be addressed in the next subchapters, *2.2.2* and *2.2.3*.

In addition to pure primary-structure weight saving, carbon composites can be seen as enablers for further energy (fuel) savings at the aircraft level in combination with flight physics and systems (cf. *Chapters 2.1* and *2.3*).

Composite parts have the advantage that they can be manufactured integrally in large free-form surfaces without gaps or rivets and thus with a high aerodynamic (laminar) quality.

High aspect-ratio wings (HARW) become feasible (cf. *Chapter 2.1.2*), and so do different fuselage concepts with integral door frames, larger frame pitches or double shell skins to integrate cabin elements.

Furthermore, with a suitable design, composite crash elements can absorb much more energy than metal structures.

Challenges

A future CAFB must be realized with a combination of adapted design principles and a new certification approach. Specifically, the challenges of a proper design for bonding must be addressed. To realize the potential of an CAFB as much as possible, several challenges of carbon composites must be dealt with:

- certifiable bonding and welding techniques for primary structures
- a new design-for-bonding approach avoiding riveting and excessive peel
- increasing the strain levels of current carbon composites for better material utilization while maintaining the "no growth" damage tolerance and no fatigue / aging advantage
- certifiable solutions for sandwich design
- significantly increasing the electrical conductivity of composites for lightning-strike protection and the electrical network
- increasing the low noise damping of the stiff and integral composite structures to avoid needing additional insulation material (cf. *Chapter 3.3*)
- large free surface forming requires adequate tools, for which the cost must be minimized
- highly integrated structural components are not easy to modify and are difficult to repair
- To further improve the cost of manufacturing as well as the environmental footprint of carbon composites, developments are also needed in the following areas:
- improved autoclave processing and infusion technology
- KI-based, online quality-controlled production processes instead of final checks offline
- development of circular-economy materials, i.e. carbon fibre and resins not based on oil
- technologies of removal, re-use and recycling (production waste and end-of-life)

Synthesis

A carbon airframe fully bonded concept may enable a primary structure to be up to 25% lighter compared to the A350 standard. From a technological point of view, most measures necessary to realize the CAFB concept are well described and understood. Detail design work and validation can be achieved in the classic development time frames for the next generation aircraft, suitable for a 2035 entry into service. All the possible improvements are generic, not limited to specific structures. Generally, composites can be built to any shape and geometry. The weight-saving opportunities mentioned below are assumptions based on the A350 technology standard. However, the final weight saving will be less because of design constraints not taken into account at the general level of consideration in this document. The reader must be aware that the savings from the different measures cannot be simply summed up because they are not fully independent from each other. To leverage the full potential of the CAFB concept, the following topics have to be addressed:

Design and stress

- Apply load-orientated layup, with *±45°* layers for shear loads (skin, ribs, spar and frame flanges, stringer feet) and *0°* layers for longitudinal loads (stringers, spar caps, etc.). Adapt anisotropic concepts, allow unbalanced layup (enabler for tailoring), potentially apply the Tsai double–double layup concept for fuselage structures Allow application of thin plies. *(-10% weight of primary structure: 0.9)*

- Remove quasi-isotropic layup and stacking rules. Today, most laminates have *0°, ±45°* or *90°* plies, a minimum of *8%* per ply. *90°* plies can be eliminated totally; stacking with two or three directions becomes easier and contributes significantly to faster manufacturing rates. *(-5% weight of primary structure: 0.95)*

Manufacturing technology

- Composite production is an additive process based on free contour tools; preferably, the production tool moulds the surface of the structural component. Deposition rates need improvement, and waste processes like vacuum bagging, long autoclave cure cycles and demoulding can be reduced as much as possible. The target for manufacturing engineering development is a net-shape and bag-free process. This will enable very competitive manufacturing costs.

- Use CFRP hybrids with thermoset and thermoplastic matrix systems for improved performance and weldability.

- Employ thermoplastic welding of system brackets (cost saving and maintenance).

- Increase the fibre content to the theoretical maximum of *70%* fibre volume, an option for simple geometry and topography and as well as for load-oriented layups.

Integration and joining

- Integral design for large structural elements is supported by means of co-curing, co-bonding, bonding, additive manufacturing and / or over-moulding for local reinforcement, enabling design for bonding (double lap and smooth grow-outs to limit peel) and improved load transfer between elements. No surface riveting to enable natural laminar flow and to avoid paint adhesion issues on rivet heads as per today. No added weight to enable riveting or a potential flush repair, full application of bonded repair schemes in service. *(-10% weight of primary structure: 0.90)*

- No aluminium means no thermal stresses and no anti-corrosion measures, like edge sealing, paint schemes and scrim plies to separate carbon and aluminium. *(-2% weight (and cost) reduction of primary structure: 0.98)*

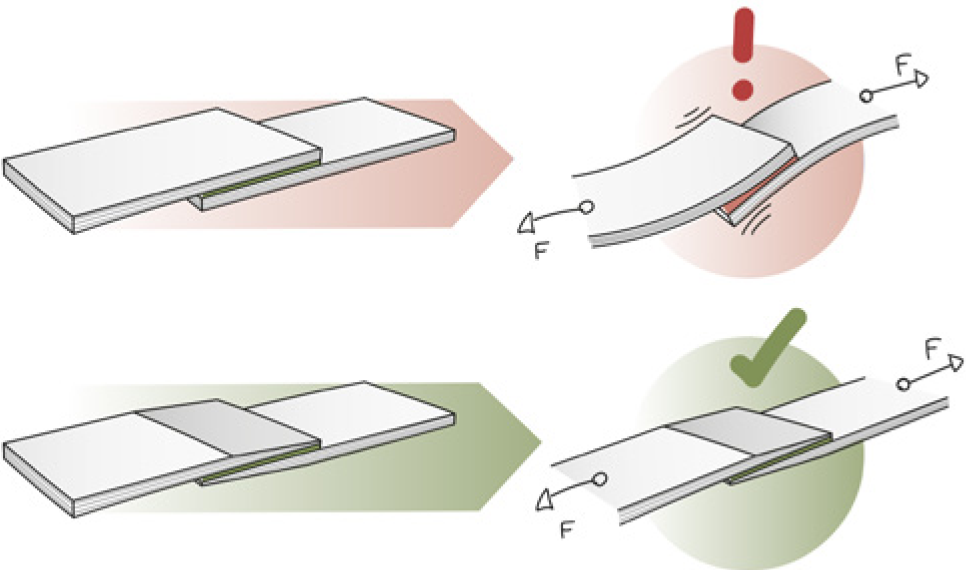

Figure 6: Design for bonding, minimizing peel loads

Add-ons

- Due to "no growth" damage tolerance, rigorous non-destructive inspections for quality-control purposes can be replaced by visual inspection, with significant cost reduction in production.

- "No fatigue / no growth" policy, no corrosion and zero-maintenance airframe significantly reduce maintenance.

- Specifically for fuselage applications, an improved sandwich bears the potential to increase the ratio between external and internal diameter. New closed-cell foams bear the risk neither of undetectable damages nor of water ingress. They bring further weight advantages and can also be used for functional integration (cf. *Chapter 2.2.3*).

Apart from aircraft performance, a low-cost carbon composite airframe can be made feasible due to adapted design, avoidance of aluminium, new quality-control concepts and advanced production technologies.

As CFRP structures do not fatigue, they also offer potential in the life cycle, e.g. for the re-use of parts (cf. *Chapter 4.3*).

2.2.2 Requirements Challenge and Use of Experience

Introduction

Large commercial aircraft have to be operated at a very high level of safety. Therefore, they need to be designed in accordance with requirements that anticipate all operational risks based on both theoretical considerations and operational experiences. These requirements are constantly updated to improve the level of safety in line with technological developments and additional operating experience.

Many requirements and permissible margins have accumulated over the decades that are historically justified and based on existing design principles. They remain unchanged, however, even when the reasons for their creation may become outdated. The need for a balanced set of requirements is central to the aviation industry. But requirements may also need to be adapted to take into account new technologies or improvements. Requirements are often retained even though they can be improved or are no longer needed. Thus, non-adapted requirements bear the risk of countering efficiency improvements.

Here, a distinction should be made between the requirements that the aircraft manufacturers themselves have established internally based on their experience and the regulations that result from certification requirements.

Internal requirements from the manufacturers are dealt with in this chapter, *2.2.2*, and the certification regulations in *Chapter 3.4*. It is clear that the internal manufacturer requirements and the certification regulations from the authorities are closely interwoven. Therefore, the separation of the chapters is not entirely clear cut. However, fundamental issues relating to certification are dealt with explicitly in *Chapter 3.4*.

As in the previous subchapter, the possible weight savings here are related to the primary load-bearing structure of the aircraft.

Potentials

The main business of structural design is calculating the behaviour of the load-bearing structure under known loads as accurately as possible and dimensioning accordingly. However, there is also the concern that there will be handling errors with the structure in production or operation. Thus, the robustness of the airframe must be guaranteed.

The robustness of the airframe is ensured in two ways: on the one hand through the manufacturer's design specifications and requirements, and on the other hand through certification regulations, for example the ultimate load factor: design for *1.5* times the maximum loads that occur during the service life of an aircraft.

It is common practice to combine the internal requirements with the ultimate load factor *1.5* from the certification for the worst-case scenario.

Several deduction factors have been introduced internally by manufacturers in the past, often referred to as **knock-down factors (KDF)**, which are used to reduce the permissible load-bearing capacity of a component. The KDFs are multiplied together for various event scenarios (temperature, moisture, damage, etc.). The result is that the structure is heavier than required by the nominal design assumptions.

In order to leverage the maximum performance, i.e. the minimum weight and cost of the airframe, it seems advisable to review the current manufacturers' deduction factors and their continued justification, or to apply possible and necessary adjustments.

To estimate the potential of a possible adaptation of KDFs, here a pure composite design is assumed without any load-bearing elements made of aluminium parts prone to fatigue.

A structure resulting from such a pure composite design will feature two main characteristics:

- Currently, no growth has been demonstrated for structures at a design strain level of up to *5000* to *6000 microstrain*. Any increase in the allowable design strain must be validated against this no-growth principle. There is evidence that the allowable strain can be significantly higher without violating the no-growth criterion. A higher elongation level can mean some per cent saving in primary structure weight.

- Allowable design values are often based on coupon tests. These values are conservatively small due to the often not-representative boundary conditions and thus lead to unnecessarily heavy structures. For example, in a structural element, impact force is mainly dissipated elastically, but the corresponding coupons are clamped. Typical deviations or defects in composite structures come with a locally reduced stiffness, causing load redistribution, hence not leading to a failure. Coupons react to the defects; coupon-based allowables are conservative and unrealistic.

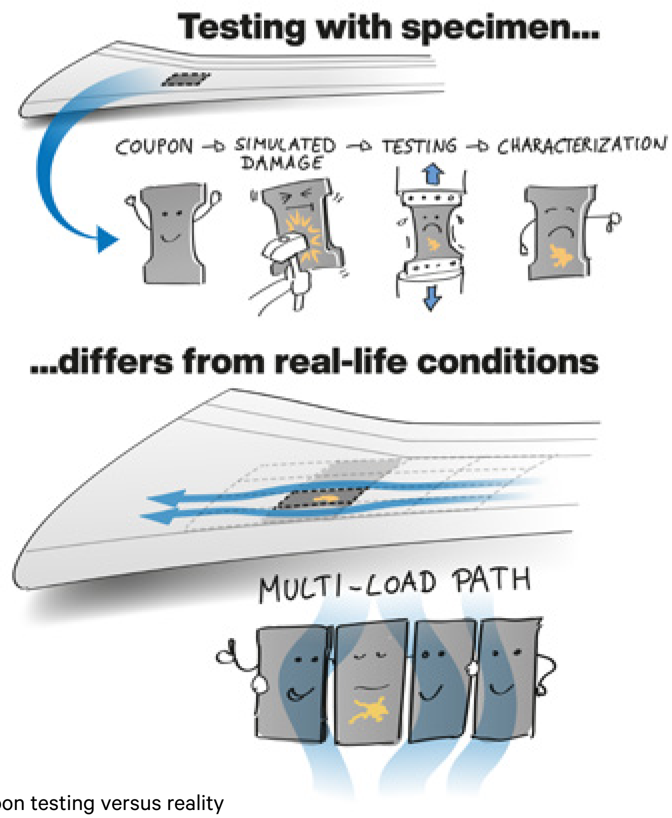

Figure 7: Coupon testing versus reality

Challenges

How far the strain level can be increased without violating the no-growth criterion still requires research and validation.

Design allowables should be derived using modern simulation methods for large structures based on models that have been validated with coupon tests. This approach is possible today but is not yet routinely practiced in the industry. For all known and possible manufacturing deviations, the effects on the strengths and on the stiffnesses must also be better determined using simulation calculations. Reducing the number of knock-down factors and updating the corresponding design rules and production regulations requires a solid data basis from aircraft operations and experienced experts.

It should always be clear that relaxation or avoidance of conservatisms in the design must be closely co-ordinated with the regulatory authorities and must never result in safety reduction.

Synthesis

A consequent **requirement challenge** may enable a primary structure to be up to another *17%* lighter compared to the A350 standard.

- Exploiting the two main characteristics of a pure composite structure (higher strain allowables and no coupon-based sizing), an adaption of the current deduction factors, mainly based on metallic experience, may leverage the potential of weight reduction compared to the A350. *(-10% weight of primary structure: 0.9)*

- The mechanical properties of composite structures depend on manufacturing technologies, but – according to experience – to a much lesser extent than initially anticipated. Manufacturing features such as variations in the curing cycle, variations in the fibre angle, porosity and out-of-plane waviness are assessed very conservatively. Either KDFs are used in the design to compensate for undetectable manufacturing deviations, or complex inspection programs are carried out during production, which increase costs. Improve allowable and design strain (no B-values, no strength-based knock-down factors). *(-5 to -10% weight of primary structure: 0.925)*

To fully exploit the possible higher strain levels and load dissipation characteristics of composites, further measures can be taken to reduce deduction factors:

- Don't combine max. temperature with max. humidity – hot airports are dry (Phoenix, AZ) and wet airports have moderate temperatures (Singapore).

- Don't use aluminium in combination with carbon composites! All the sealing requirements with additional weight and – more importantly – additional production cost and maintenance effort can be simplified without an aluminium mix.

- The reserve factors are between *1.1* and *1.3* in many areas but could be closer to *1.0*. They are determined by the manufacturing conditions, production costs and design rules (thick layers, stacking sequences, stacking rules, symmetry requirements in the layup).

- Many systems in an aircraft require supply lines that must be attached to the supporting structure using brackets. There are often rules for the distances between the systems that take up space and require separate brackets. This results in additional weight and increased installation effort. Therefore, these distance rules should be reviewed as to whether they apply similarly on composite structures or whether they can be relaxed.

- Sometimes approval requirements are interpreted more strictly than required. For example, according to certification requirements *CS25.365*, the fuselage only needs to be tested at *1.33* times $\Delta p+$ relief valve setting, while internal requirements may require a test at $2\,\Delta p$. As a result, the structure has to bear higher loads than necessary and will accordingly be designed with more thickness.

Due to the efficiency increase in design and reductions in manufacturing cost, weight, fuel consumption and maintenance effort in service, the challenging of requirements as sketched above offers an attractive package of improvements. However, it has to be absolutely clear that such challenging must always be conducted under the strict boundary conditions of maintaining or even increasing the current level of safety.

2.2.3 Integrated Airframe Structure

Introduction

The basic idea of integration is to improve overall efficiency by using components that were previously not load bearing for load transfer, by making structures inherently adaptable to off-design conditions and by enabling additional functions, accommodating them in the structure.

The load-bearing (primary) structure of a modern midrange aircraft accounts for about *40–50%* of the total operating weight empty (OWE). About another *30%* of OWE is made up of components that have no load-transfer function, like fairings, or serve other needs, like systems, cabin, installation, insulation, lightning protection, etc. The possible weight savings in this subchapter relate to the *30%* OWE that is not attributable to the primary load-bearing structure.

How much weight saving and/or performance increase can be gained in a midrange aircraft if previously non-load-bearing functional elements are integrated into the load-bearing primary structure?

Potentials

The **combination of load transfer and other functions** is not new: for example, wings are fuel tanks at the same time, fuselage substructures also serve as impact / fire protection and a CFRP fuselage structure also partially takes over the thermal insulation function, while metal structures have the inherent capability to serve as electric grounding and electromagnetic interference (EMI) shielding.

There are different pathways to leverage the full potential of function integration, and listed by increasing complexity, these are:

- giving secondary structures more integrated functionalities,
- switching secondary structures to the primary structure,
- integrating passive functions into the primary structure,
- adding active elements to the primary structure, and
- integrating active elements into the primary structure.

Additionally, it should be noted that function integration may achieve an increase in aerodynamic performance without additional or with minimum weight increase, e.g. systems for active flow control or morphing structures.

Challenges

The biggest challenge for a function-integrated airframe structure – especially for active function integration – is the reliability of integrated components: it must not happen that the failure of one function necessitates the replacement of the entire component. The failure probabilities of the individual components must be considered in the design.

Additional functions relevant to flight safety may not be integrated. And a concept must be developed that makes a local functional failure as unlikely as possible and does not limit the function of other components in an emergency. This is why the integration of active functions into the airframe will require even more development time and testing than the integration of passive functions and secondary structures.

The operation and in particular the maintenance and repairability of function-integrated structural components is challenging, and the decommissioning and de-integration of the functions and materials involved requires new technologies.

Another challenge lies in the organization of the approval regulations into the Air Transport Association (ATA) chapters. If several systems (ATA chapters) are integrated in one structure component, the responsibilities must be combined. It is uncertain whether this will succeed formally. Attempts with multi-ATA brackets in previous aircraft have shown the challenges associated with combining separated ATA responsibilities.

Function integration into the airframe does not represent the optimum for the individual function, but the overall system should benefit from the chosen compromise. An overall reduction in weight and/or an increase in performance through the integration of other functions is therefore only possible if the individual disciplines are willing to compromise in order to subordinate themselves to an overall system optimum. Thus, function integration represents a formidable challenge to the conventional engineering mindset, which must be overcome.

Synthesis

The general pathways for leveraging the potential of function integration were listed above. For each of these pathways, the following technological options may be pursued:

- Secondary structures with more **integrated functionalities**
  - Active noise-damping elements can be integrated into the cabin lining to avoid heavy acoustic insulation materials, which today may add weight significantly.
  - LED displays integrated into the cabin lining may help to avoid windows, which would clearly save weight on the order of tonnes and improve the aerodynamic performance of the fuselage. Passenger acceptance could be developed by initially closing individual windows with LEDs and offering seats at slightly lower prices.

- **Switching secondary structures** to the primary structure
  - Designing doors in the fuselage to be load bearing has some implications for the emergency doors but is an efficient measure for reducing the weight.
  - The further development of repeatedly detachable load-transmitting joining and contacting technologies, e.g. thermoplastic welding, is essential for a successful integration of secondary structures into the load path:
    - With new welding technologies the cabin lining and the outer skin of an aircraft fuselage can (possibly partially) form a load-bearing double shell, which would make it possible to reduce the internal support structure, e.g. the stringers and frames.
    - Fairings can also be used to transfer loads between the fuselage and wings to a certain extent, thus relieving the primary structure. Certainly, then they must be treated as primary structure, including related maintenance and inspections.

- **Integrating passive functions** into the primary structure
  - It is possible to substitute heavy passive parts with thermal insulation by load-bearing structures. The use of CFRP materials may reduce the amount of insulating material, for example.
  - Non-load-bearing metal for the electrical structure network (ESN) can be saved by means of electrical conductivity integrated into the CFRP (threads, nonwovens, wires, foils).
  - Integration of electrical systems (e.g. communication networks) into the load-bearing primary structure is possible, provided the robustness of the electrical contacts to the electrical power supply and consumers is guaranteed. In terms of production technology, the integration of thin steel foils or metal wires into a fibre composite is now ready for automation. This would save weight and, even more, assembly cost, but the impact to repairability must be minimized.

- **Adding active elements** to the primary structure
  - The integration of active elements into structural components is certainly very ambitious and will require even longer technological development in some cases, but can reduce the complexity and weight of current systems (e.g. ice-detection sensors or wireless information transmission thanks to energy harvesting).

- **Integrating active elements** into the primary structure
  - Morphing capabilities of structures to adapt to off-design conditions (e.g. angle-of-attack adjustments in engine intakes or small changes in the shape of flaps

and winglets) may sound futuristic but are in principle possible when integrated into fibre composites with functional materials.

- New functional elements will be needed in the future to further reduce aerodynamic drag (ref. *Chapter 2.1.1*). Hybrid laminar flow control requires new structural concepts that enable active suction. Here, technology demonstrators need to be further developed. The related new systems will generate additional weight in the airframe, which can be minimized by integrating them – at least partially – into the load-carrying structure.
- SHM system to first improve maintainability, then reliability and re-usability and finally weight.

A function-integrated design may save both weight and space. In a fuselage shell constructed as a double-shell sandwich, for example, a metallic foil can be used as the outer skin for EMI and lightning protection as well as for optical impact detection. The core material serves as a system support and for thermal and acoustic insulation, reinforced by longitudinal beams for the longitudinal loads of the structure. The inner skin bears the circumferential and shear loads of the fuselage and is provided with printed or integrated conductor tracks. The inherent bending stiffness of the double shell allows the frame height to be reduced. Repeatedly detachable adhesive joints are used for cabin monument installation and for maintenance.

Some technologies – structural bonding, integration of metal foils, integration of an SHM system into a CFRP structure – are ready for introduction. Some others need further development and might not be ready for the next-aircraft generation. But in any case, for function integration, new certification processes need to be established.

The pure weight-saving potential of all measures combined is estimated at *5%* from reduced OWE without landing gear and engine (factor of *0.95*), depending on the maturity of the different options.

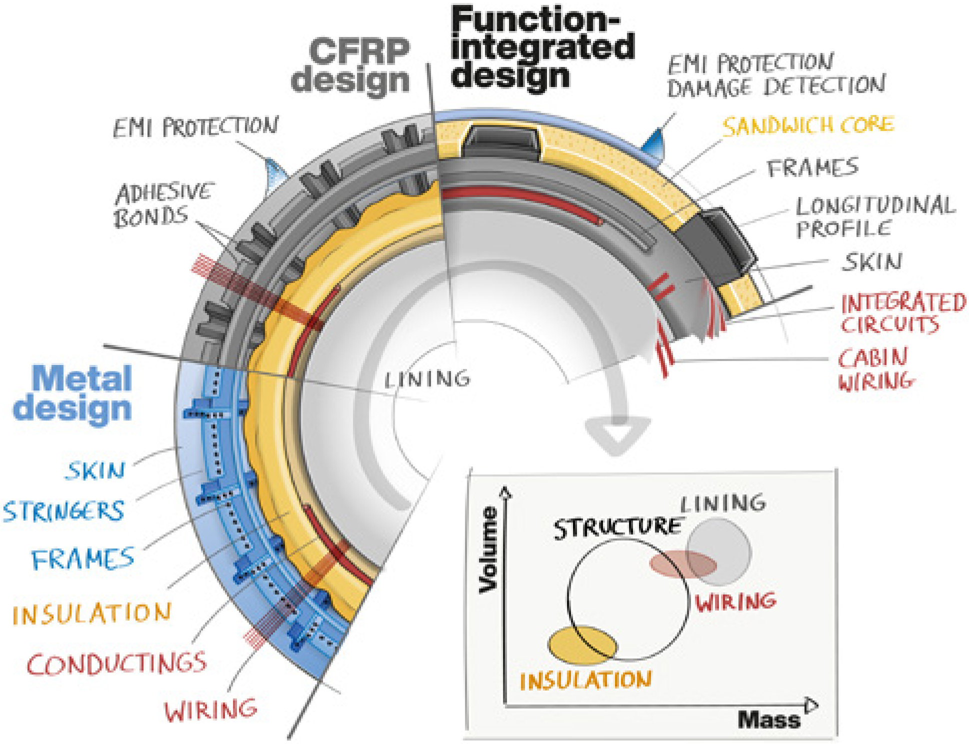

Figure 8: Functionally integrated fuselage structure saves weight and cabin space

2.3 Aircraft Control

Introduction

Future sustainable aircraft will be characterized by a drastic reduction in energy consumption, driven by ecological as well as by economic reasons. The necessary reduction of aircraft drag and weight requires careful management of the acting loads and structural responses. One way to achieve this may be to continuously and completely monitor, assess and subsequently control the actual flight state. For such an **ultimate aircraft control (UAC)**, two main pathways have to be followed in parallel:

- control of all loads acting on the aircraft structure and systems, and
- control of the aircraft flight dynamics.

The former shall lead either to significant weight reduction or to the realization of more efficient structural and systems concepts. The latter shall actively limit flight states, which become critical for sizing the aircraft configuration and components related to flight dynamics (movables, tails, etc.). This aims to decrease or even annihilate any trim drag and adapt the aircraft to all flight conditions while maintaining the highest flight efficiency. Technically, load control and control of flight dynamics should always be treated in a coupled manner, since changing aerodynamic loads will impact flight dynamic stability and vice versa.

Potential

The main target of controlling aerodynamic loads is the reduction of structural weight, especially with respect to the wing. Wings are designed such that besides generating the necessary lift at minimum drag, they shall be able to withstand all loads expected during flight and landing (ground loads), and the requirements from these loads on material strength and stiffness subsequently influence wing weight. Thus, alleviation of these requirements will directly lead to weight reduction, and the corresponding concept of load alleviation has been well known and partially applied for quite some time. **Load alleviation** is realized by passive concepts like aeroelastic tailoring through design of favourable wing-bending and torsion properties, by the wing planform and general structural architecture itself, by advanced structural design concepts (CFRP), and/or by active concepts using conventional control surfaces to redistribute aerodynamic forces. To date, however, the concept of load alleviation has shown some progress, but there is still considerable potential for further developments. Therefore, it is essential to estimate the theoretical potential of load alleviation under ideal conditions to justify additional investments in research and development: in the most ideal case, a wing would be designed for the *1 g* load case only, i.e. straight and undisturbed cruise conditions, and appropriate load-alleviation techniques will have to adapt the wing such that aerodynamic loads are redistributed to keep the *1 g* wing root-bending moment. As outlined in the section on drag reduction, the other potential of load alleviation to be exploited is to enable the realization of more efficient aircraft structures like, e.g., cantilever wings with aspect ratios of up to *20*. This will reduce induced drag by a factor of about two.

Load control will lead to highly elastic structures, which will not only severely influence deformation at varying flight conditions but also critically impact the flutter characteristics of the wing. Additionally, the flight dynamic stability properties of the complete aircraft will be ultimately affected. Thus, advanced load control has to be accompanied by corresponding **control of flight dynamics** to realize highly elastic aircraft. Complete control of flight dynamics will also make it possible to reduce natural flight stability, enabled by advanced control loops, such as have been proven, e.g., on military aircraft. This may reduce or even eliminate trim drag, which in cruise flight may account for about *1–2%* of total drag, and which especially at take-off requires substantial engine power to counterbalance the aerodynamic moments of the high-lift system. Additionally, a thorough combination of load and flight dynamics control will allow the continuous adaptation of the aircraft configuration for most efficient flight during a mission, considering not only the design point but also operations in off-design. This flexibility will be of benefit for novel trajectory operations, e.g., with environmental constraints on cruising altitude to avoid atmospheric regions of high contrail formation.

Challenges

Today's modern civil aircraft already apply load alleviation for manoeuvre load cases and gust load cases. One of the key challenges or limitations is currently certification, as any load-alleviation functionality has to be operational before take-off in order to classify the aircraft status as dispatchable. Hence, the reliability of such systems is a key challenge and for some systems still an obstacle. Due to today's limitations w.r.t. certification, systems, sensors, etc. the full potential has not yet been explored.

Passive load alleviation may, for example, be achieved by using highly flexible wings. But high flexibility reduces the effectiveness of the outer wing control surfaces, i.e. the ailerons. Ailerons and spoilers are the key control surfaces used in today's modern aircraft for load alleviation in manoeuvre cases as well as for gust cases. Especially for active gust load alleviation and active flutter control, very fast-reacting control surfaces are required, as well as precise and fast sensors.

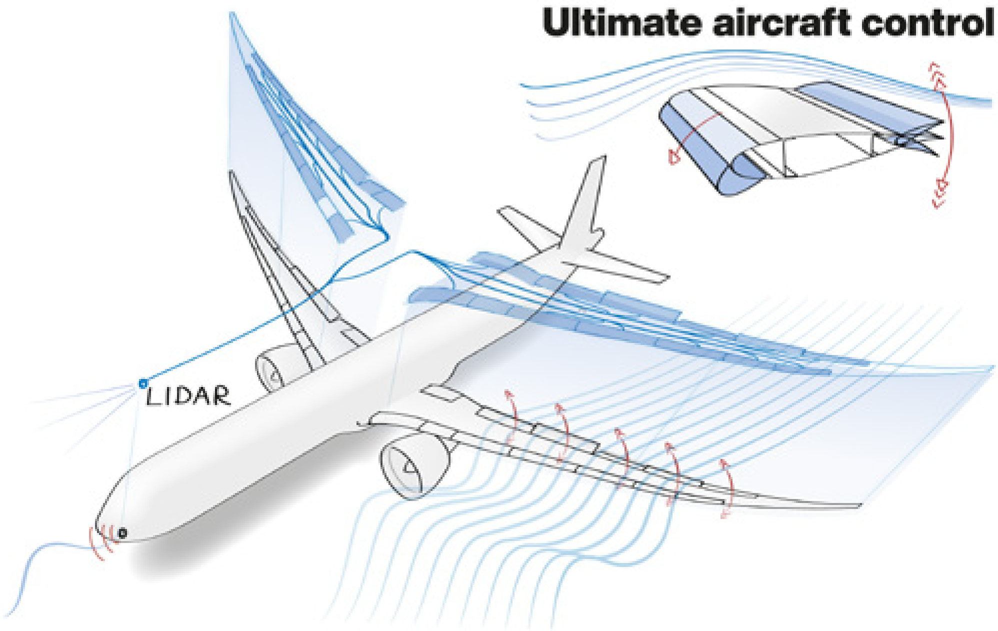

Figure 9: Fast close-coupled sense-and-control loops allow real-time adaptation of the component shape to minimize loads

Highly dynamic compensation systems for gust loads have already been developed some 30 years ago, but they still lack elevated-frequency gust detection systems suitable for practical application. For higher dynamics and an extended envelope of load alleviation, substantially improved systems are required where the issues of reliability and certification need to be solved. Alternative solutions to classic control surfaces may yield further design degrees of freedom: pop-up spoilers or active flow control means to trigger separation could potentially overcome the limitations of classic devices on future wing layouts with too-limited installation space on the outer wing. An important challenge of future, more flexible wings is the control of the wing torsion moment. It appears that this requirement of ultimate aircraft control can only be achieved by employing leading-edge flaps as an effective means for varying the pitching moment independently of the lift. This calls for extremely fast flap actuation beyond the current state of the art.

For control of flight dynamics, similarly as for load alleviation and flutter control, reliability and subsequent certification pose the main challenges when natural flight stability is partially or even completely reduced. Here the situation may also appear that the given certification requirements are inappropriate to advance future technological solutions, thus limiting potential benefits through an inherited over-conservatism in the regulations. Technically, flight dynamics control with reduced stability is already realized for military fighter aircraft to enhance manoeuvrability as well as aerodynamic efficiency, and for civil aircraft in some cases trim tanks are used to shift the aircraft centre of gravity backwards for reduction of trim drag during cruise flight. However, especially due to limitations in reliable overall flight-state assessment and associated rapid control systems, certification for civil operations poses a severe hurdle. In total, for all future advanced flight-control concepts, a proper consideration of the potential performance benefit versus the complexity and reliability challenges has to be thoroughly conducted.

Synthesis

Aircraft must sustain aerodynamic forces covering the whole spectrum of the load envelope. For load alleviation, the "critical corner points" of the envelope with the highest loads at low and high speeds need to be identified. When addressing the corresponding technological issues, research efforts have to progress in sequential order. First, physical viability and technological effectiveness need to be clarified: is it possible to locally generate lift forces in the required frame of magnitude and time, and can efficient sensor, control and actuation systems be devised? Then, if the achievable reduction in total weight is large enough or if the now-possible new structural layouts offer high enough efficiency, in a second step the reliability of the necessary systems has to be brought to a level that fulfils certification requirements. If this can be achieved without compromising system weight and energy consumption, load-alleviation technologies will find their way into industrial application. It is essential to adhere to the proposed sequential order: raising reliability concerns upfront may prematurely limit the size of the technological solution space. Potential technologies, which justify later efforts for maturation, may not be considered at all.

To leverage the full potential of aerodynamic load redistribution, firstly the interplay of passive aeroelastic tailoring and active load-alleviation concepts must be fully understood, especially when using CFRP materials. Second, different means of load redistribution, e.g. mechanic control devices at the wing trailing and leading edges, flow control to temporarily increase local maximum lift beyond steady-state values combined with targeted triggering of flow separation for lift reduction at other locations, etc., must be analysed with respect to the time-dependent forces and moments to be produced and the actuation power required. Third, control strategies have to be devised, which include state monitoring of flow and structure, by e.g. laser imaging detection and ranging (LIDAR) devices and structural load monitoring (SLM) strategies, to enable an accurate state assessment from which the necessary load redistribution can be derived.

The principle of load alleviation through redistribution of aerodynamic loads relies on the assumption that the wing root-bending moment caused by aerodynamic forces represents the driving mechanism for the structural sizing of the wing. Therefore, it has to be shown in detail whether the critical corner points found in the load envelope really represent the critical cases for load-alleviation concepts, or other additional aerodynamically governed cases have to be identified as critical. When reducing aerodynamic loads more and more to lower the requirements for sizing the wing structure, other constraints may become dominant. Thus, it is critical to identify these other constraints in a hierarchical manner, i.e. in the order in which they become critical when successively reducing aerodynamic loads. These critical cases need to be assessed to stimulate additional research efforts in other disciplines to remove the corresponding constraints.

A “critical point” in the flight manoeuvring envelope is given by the upper left corner, since here the stall boundary and the *2.5 g* limit load boundary match. At this point, any lift redistribution for load alleviation will have to reduce manoeuvrability, with the required loss of manoeuvrability depending on the desired load reduction. To still retain acceptable manoeuvrability, a reduction of the wing root-bending moment by *33%* may represent a pragmatic choice for initial practical implementation. According to CS-25 certification requirements, the limit loads have to be multiplied by a safety factor of *1.5*, then calculating ultimate loads at *3.75 g*. Reduction of the *2.5 g* limit with a load-alleviation system by *33%* to *1.67 g* will lead to an ultimate manoeuvre load limit of *2.5 g*, supposing that, following CS-25, a sufficiently low probability of failure for the load-alleviation system allows a safety factor of *1.0*.

Ultimate aircraft control, i.e. the complete and simultaneous control of aircraft loads and flight dynamics, requires comprehensive, accurate and instantaneous acquisition of all relevant flight data, globally as well as locally. The processing of global and local actual flight-condition data will enable the targeted determination and implementation of dedicated measures to deliberately reduce the acting loads and control the flight state. Such requirements lead to the concept of a sensor-based aircraft, where physical parameters like local surface pressures recorded at optimized locations will be blended with “classic” flight data from, e.g., angle of attack (AoA) sensors and pitot tubes, and with a “digital twin” model fed by numerical data from real-time surrogate models. Thus, instantaneous assessment of all actual flow states and loads may be possible, paving the way for local flow control measures for load reduction or enhancement of local flow properties, as well as for direct and accurate flight-state control when relaxing or completely giving up natural flight stability.

These considerations set the stage for successive steps to achieve ultimate aircraft control:

- The first step is represented by the **blending of flight data** from current air-data systems with data from a suitable "digital twin". For the required sensor and computer technologies combined with artificial intelligence (AI)–supported numerical modelling, *TRL 6* can be reached within five years. Another *2–5 years* may be required to reach certifiable maturity so that current air-data systems can be augmented or even be replaced as the prior data source.

- The second step should aim at the **reduction of the wing root-bending moment** up to *33%* through load alleviation. This will require substantial progress in actuator technology and systems design to account for all failure probabilities. Under optimistic assumptions, this will require about *15 years* to reach *TRL 6*; certifiable maturity may require another *5–10 years*.

- Further steps with **more aggressive load and weight reduction** will depend on successfully mastering the first and second steps, making it possible to reach *TRL 6* in 2050 or beyond.

Ultimate aircraft control with extreme load alleviation may be regarded as a prerequisite for substantial aircraft weight reduction and/or realization of radical, more energy-efficient structural concepts. It is essential to have in plain view that the realization of such drastic load-alleviation technology requires a truly multi-disciplinary technological research and development effort. Only by deliberately interlinking aerodynamics, structure, flight mechanics and systems may the possible potential come into reach. Furthermore, since highly critical aircraft components will be altered in their basic characteristics, it will be absolutely mandatory to adhere to the sequential process of advancing from one level to the next (cf. *Chapter 3.4*).

2.4 Propulsion System Integration

Introduction

Unlike what the term might suggest, propulsion system integration is not only the combination of the aircraft and propulsion systems according to their individual designs, but rather a full discipline that must be pursued consistently along the entire design and technology definition route. Thus, an optimum integration is the result of close co-operation and iterations between airframer and engine manufacturer initiated during the preliminary design phase. Today it is recognized as a fully coupled integrated discipline starting from the conceptual design stage and trying to generate benefits from synergies or at least from the reduction of unnecessary surcharges and of uncertainties through high-fidelity modelling of integration effects and interfaces. In parallel, such modelling and analysis of propulsion system integration must also identify risks arising from integration effects and thus lay the basis for risk mitigation. Accordingly, a detailed consideration of integration effects typically has repercussions for the entire configuration. Historically, this can be demonstrated by the integration of UHBR (ultra-high bypass ratio) propulsors on low-wing aircraft configurations or interactions between propulsion systems and wing or tail control surfaces. In the future, such feedback effects will become even more significant if, for example, technologies such as boundary layer ingestion or active flow control are used. Hence, the propulsion system integration of the future will require fully coupled and highly accurate methods that at least describe the aerodynamic and performance-relevant interaction effects in design and off-design of both the airframe and the engine.

In the light of potential new propulsion technologies, the basic propulsion system requirement of providing the necessary thrust to the aircraft without failure in any of the flight or atmospheric conditions still remains. These conditions must include the entire aircraft attitude and speed domain as well as all atmospheric influences (water, ice ingestion) and aircraft operability requirements as typically defined by aircraft certification specifications (FAR25 / CS25). The same applies to engine off-design, sensitivity and operability, in particular regarding inlet distortion and crosswind capability but also with respect to engine failure assessment as defined in engine certification specifications (CS-E). These include environmental requirements. At the end of any pre-development phase for a propulsion system, including its integration, both the aircraft and propulsion system definitions must be frozen and the knowledge of their characteristics accurate enough to guarantee fulfilment of all requirements.

In general, the physics of power conversion in a propulsion system consists of several conversion steps, which differ depending on the basic propulsion system architecture. Nevertheless, a division into internal conversion steps and the corresponding efficiencies and external conversion steps can be done, which is meaningful. For gas turbines and their related thermodynamic cycles, internal conversion describes the step from fuel to kinetic and thermal gas power (thermal efficiency). This is followed by a conversion into mechanical shaft power using turbines (transmission efficiency). For a fuel cell–based system, the internal conversion is characterized by the fuel cell efficiency, including consideration of the required cooling, while for battery-based propulsion, on top of the electric motor efficiency, the battery charging and de-charging losses and the power electronics losses need to be considered. In any case, the resulting shaft power is the input for conversion into kinetic fluid energy or jet power using a fan or open rotor (propeller). This jet power is converted into flight propulsion power via the kinetic propulsive efficiency.

Propulsion system installation effects including weight will predominantly act on the fan or open-rotor efficiency but can also affect the kinetic propulsive efficiency, e.g. due to non-uniform velocity or pressure distributions within the jet. Beyond these dominating foreground effects, several subsystem integration and coupling effects besides pure propulsive power generation have to be considered (e.g. power off-takes via bleed or electric power). In addition, the future propulsion system installation and accessibility including potentially new subsystems such as cooling and thermal management components should be such that maintenance checks during operations are made easy.

The following subchapters only address the **potential and challenges of propulsion systems integration** acting on the fan / open-rotor and kinetic propulsive efficiencies. The internal efficiency of the individual propulsion system will not be discussed.

2.4.1 Ultra-High-Bypass and Open-Rotor Concepts

Potential

Increasing the fan mass flow and thus the bypass ratio (BPR) to improve the external kinetic propulsive efficiency was an obvious trend during the last four decades of turbo-fan-driven aircraft design. With higher fan or bypass mass flow, the specific bypass thrust and exhaust velocity can be reduced. In parallel, more kinetic core energy is transferred via the turbine to the bypass, leading to reduced core jet exit velocity. Both effects directly lead to increased kinetic propulsive efficiency but also introduce pressure losses in the ducts. Thus, increased bypass ratios for higher efficiencies are physically coupled to high mass flow and as such to higher engine diameters. Although the correlation between efficiency gain and required fan size is increasingly flattening out, a further increase in BPR above the actual level of *10–12* is still feasible. Solely via the kinetic propulsive efficiency, higher BPRs up to *17–18* offer approximately *3–6%* in total efficiency gain, which might be reduced by nacelle and internal pressure drag penalties, as well as by powerplant system weight and interference drag penalties.

Open-rotor concepts (OR) as well as **contra-rotating open rotors (CROR)** offer an even higher potential in kinetic propulsive efficiency (*10–15%*) due to their further increased mass flow and thereby reduced specific thrust. In addition, such concepts avoid penalties like mass and drag increase from the nacelle, but on the other hand they have to overcome the associated drawbacks such as noise, large diameters, weight and blade loss containment. Between ducted UHBR and OR concepts, there might be room for shrouded fans with very slim / short nacelles. However, their individual optimum as a compromise between the above-mentioned advantages and drawbacks has to be carefully analysed through the whole flight envelope.

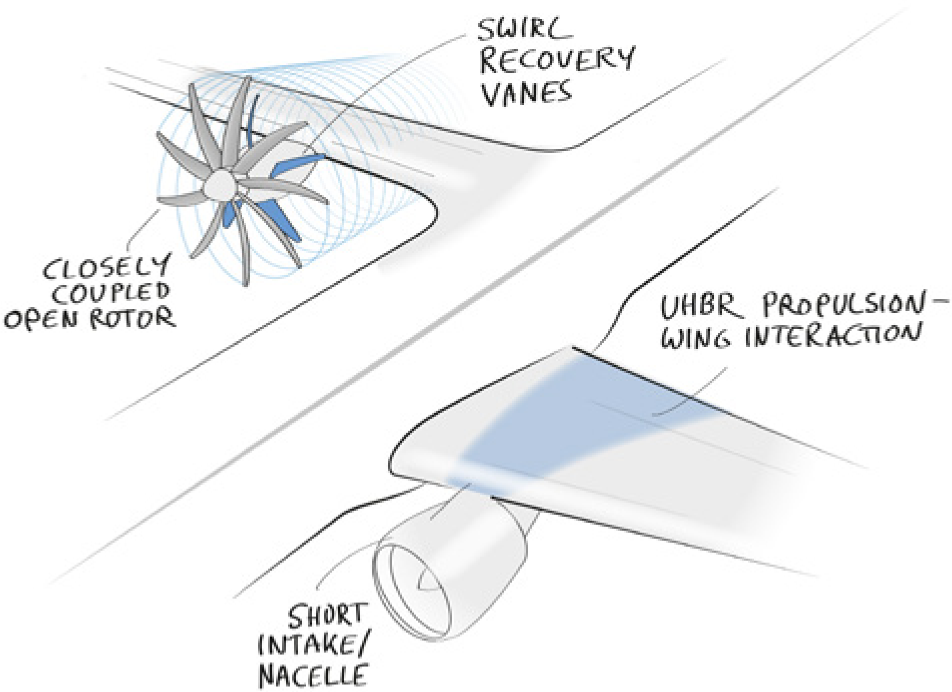

Figure 10: Highly fuel-efficient engines cause strong integration challenges for the overall aircraft configuration

Challenges

Increasing the propulsor's diameter obviously already amplifies the classic installation effects in terms of the integration of larger diameters from aerodynamic, geometric, structural, and weight and balance perspectives. While smaller BPR do allow for several conceptual engine hoist points (different fuselage positions and different wing positions), UHBR concepts are typically restricted to inboard wing positions and rear fuselage positions. In both concepts, a closer aerodynamic coupling due to closer distance has to be fully analysed and assessed for design and especially for off-design operating conditions, since, e.g., angle of attack, cross-winds but also higher wing circulation (high-lift configurations) increase the aerodynamic interaction. Additional measures (high wing, gull wing, etc.) are certainly required to make it possible to host engines with BPRs above *15* and open-rotor concepts in future aircraft concepts. Special attention has to be paid to the mounting concept to find the best compromise in terms of weight within the perimeter of the engine-plus-pylon structure, while minimizing flow distortion effects. Aside from the diameter, the streamwise dimension also bears additional challenges: For OR and CROR concepts the increased diameter leads to a shorter axial distance between rotor and wing, assuming that a higher diameter is not offset by a further forward rotor position. This will bring future large OR and CROR concepts into relative installation positions that have recently been investigated with a focus on distributed propulsion (c.f. *Chapter 2.4.3*). From an aerodynamic and aeroelastic perspective, the reduced distance leads to higher unsteady interaction effects affecting the rotor (upstream wing effect) as well as the wing (downstream rotor effect). Also, the drag increase due to propeller–wing interaction along with any interaction effect with pylon structures have to be carefully evaluated.

For shrouded concepts, the adverse trends from intake sizing have to be overcome. This requires "de-coupling" intake length scaling from its diameter to counteract an increase in drag and mass. This basically requires shorter intakes (e.g. intake length / diameter in the range of *0.40–0.55* rather than *0.60–0.70*). Such short intakes are known to be aerodynamically "more aggressive" and bear a potential higher cross-wind sensitivity. Due to the relative length reduction, the inner flow structure (e.g. position of peak Mach number and its following diffusion rates) will also be altered, which again requires full understanding and analysis, since experience from "geometric scaling" cannot be deployed. This can be counteracted by new design methods that take into account, e.g. more detailed knowledge about the intake–fan interaction, but also by using active flow control techniques specially to control the off-design behaviour.

Open-rotor concepts as well as contra-rotating open rotors do in principle avoid the intake problem and thus allow high propulsion-efficiency gain without such drawbacks. While CRORs offer another degree of freedom in the design thanks to a load shift between the rotors and thus can be designed to be less sensitive to the influence of cruise speed on efficiency, they still suffer from disadvantageous noise behaviour compared to UHBR concepts, with their noise-shielding ability. OR concepts with a stationary outlet vane row reduce the noise problems via a reduced relative speed between the two rows. In parallel, due to the missing casing and thus containment option, OR and CROR concepts require a viable blade-off solution. This can also only be solved with a combined approach using or modifying the aircraft structure to mitigate the associated risks.

Synthesis

Realizing a higher propulsive efficiency via reduced specific thrust but higher mass flow through the propulsor and thus increasing its diameter (or bypass ratio if a core engine is still present) appears to be an inevitable development, since it offers further valuable gain in total efficiency. All concepts, whether UHBR (geared or non-geared), OR or CROR, do share some of the challenges related to the large propulsor size and its inherent closer coupling to either wing or fuselage. However, tackling these challenges through a more detailed knowledge of the aerodynamic and aeroelastic interaction mechanisms and sensitivities should lead to a holistic design with minimum drawbacks. For some aspects, e.g. BLI (see *Chapter 2.4.2*), this close coupling interaction may even offer some benefits. Consequently, the deliberate use of a holistic integrated design will have to consider and compensate for such effects of close coupling. This will be required for wing designs using, e.g., high wings or gull wings to allow for more propulsion system space, as well as for a more distortion-tolerant fan to make use of boundary layer ingestion (see *Chapter 2.4.2*). In addition, typical cross-over disciplines such as noise mitigation and shielding but also structure-borne noise related to engine vibration can only be addressed through a holistic approach, e.g. by realizing downward wing shielding for reduction of propulsion noise emissions.

2.4.2 Boundary Layer Ingestion

Potential

The use of boundary layers with their reduced momentum or energy to allow the propulsion system (typically the fan or propeller) to perform the momentum increase at a higher efficiency level potentially enables higher overall efficiency for the propulsion system. Such **boundary layer ingestion (BLI) concepts**, sometimes also called wake filling, have been widely studied in the past decade. In general, BLI concepts can be deployed for wing as well as for fuselage or tail-related boundary layers (BL). Since a typical fuselage BL represents about *20–25%* of the total aircraft drag, rear fuselage integration offers the highest potential. Such concepts typically place the engines either side by side (*BLI 180°*) or axisymmetrically at the central rear fuselage (*BLI 360°*). The prediction of the BLI benefits, from a basic fluid mechanics point of view, is rather easy, only relying on size and momentum loss in the BL, and can theoretically reach double-digit efficiency gains. For a complete system integration instead, the adverse effects, which are mainly the fan or propeller performance impact but also additional effects from a more buried engine integration from the structural and aerodynamic aspects, have to be considered, reducing the potential to a single digit. The highest overall performance increase is obviously achievable for aft-mounted *BLI 360°*, where the BLI propulsor is sized to only act on the boundary layer to reduce the efficiency penalty in undistorted flow, while other (main) propulsors, e.g. in underwing installation, generate the main thrust (*>80%*). In conceptual studies, such concepts have shown block fuel improvement potentials above *10%*, but as described above, penalties related to the fan inflow distortion as well as reduced Reynolds numbers might downgrade the potential significantly and have to be quantified using higher-fidelity methods. For propulsors with a reduced mass fraction originating from boundary layers, due to a partial boundary layer, e.g. from the wing or mid-fuselage, the expected block fuel effect can be considered in the range of medium to upper single digits (*4–8%*), where reductions are mainly caused by additional power conversion losses. In all cases, the AFC power demand has to be considered in the overall efficiency calculation.

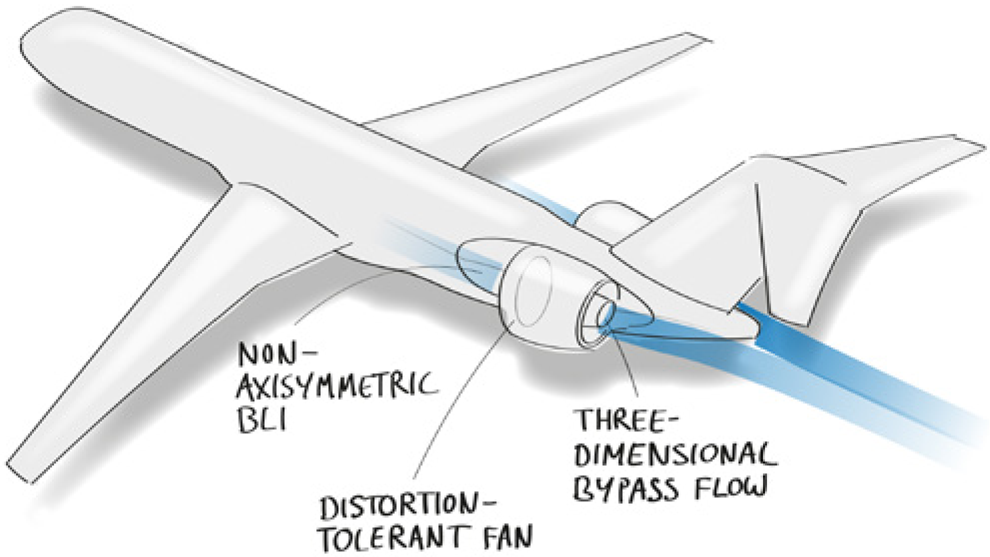

Figure 11: Advanced UHBR engine integration on the rear end, exploiting the synergies with boundary layer ingestion

Challenges

The inlet design for a high-cruise-speed propulsion system is already a complex task from the aerodynamic perspective, since it has to combine low losses and high flow uniformity at high cruising speeds, where the inlet needs to decelerate the flow with high-flow turning angles at low speeds. In a BLI setting, the inlet also has to capture a large share of the fuselage's low-momentum flow and cope with an additional dimension of flow non-uniformity. This in general means significant changes to the entire configuration and not just the propulsion system. The fan inlet geometrically must be merged with the surface generating the boundary layer, preferably the fuselage, while the according inlet stream tube has to be designed for the different flow characteristics and reduced diffusion. This generates a multi-criterion design task including the entire fan. In general, fan aerodynamics can suffer from inhomogeneous intake flow, resulting in a mass flow reduction of up to *15%*, and the increase of fan diameter and weight to maintain the thrust, with a reduction of the stage efficiency of the fan of *1–2%*. Hence, the balance between the BLI potential and the fan penalty has to be carefully designed with respect to energy savings, but also with respect to aerodynamic and mechanical stability at low aircraft speeds, high angle of attack and sideslip. The latter effects especially have to be mitigated by a distortion-tolerant fan design. For BLI rear fuselage fans with their high hub-to-tip ratio, on the one hand smaller impacts on pressure rise and efficiency due to the effect of the boundary layer can be considered, while on the other hand the off-design sensitivity may increase, e.g. during cross-wind conditions, due to the very complex flow structure on the lee side of the fuselage acting on the full annulus height. Special attention has to be paid to the stator design for both circumferentially symmetric and especially circumferentially asymmetric BLI since, for the latter, the operating-point-dependent circumferential turning of the inlet distortion by the rotor has to be carefully taken into account.

In addition, aeroelastic design aspects of the fan stage play a significant role because of the large variation in flow conditions, especially self-excited oscillations and flutter risk. In combination with the aero performance, this again demands a detailed design along the full operational range of the BLI propulsion system, rather than just determining the benefits at cruise.

In particular BLI systems that are tailored to act predominantly on the boundary layer and thus deliver approximately 1/3 of overall power compared to UHBR engines (e.g. the mentioned rear fuselage fan) are only feasible in combination with electrical or hybrid onboard energy systems and electric motors, since for such a BLI fan driven by a small gas turbine, all benefits would be suppressed by the scale effects of the small gas turbine.

Synthesis

Although counteracting effects such as, e.g., fan efficiency and operational-weight-empty penalties reduce the BLI net effects, it still offers interesting potential. Realizing this potential requires a fully multi-disciplinary design approach that takes aircraft aerodynamics, propulsion aerodynamics and flight physics fully into account. In particular the detailed characterization of the aerodynamics to assess BLI requires a seamless, "interface-free" setup between the outer (airframe) aerodynamics and the inner (propulsor) aerodynamics. Historically the AIP (aerodynamic interface plane) has been used to describe the coupling of intake and fan using reduced order parameters like local total pressure distortions (DC60) or non-uniform radial or circumferential flow structures (described by, e.g., radial distortion index [RDI] and circumferential distortion index [CDI]) in combination with the total pressure loss. Such simplified characterizations are not at all capable of dealing with the complex nature of BLI flow and fan interaction. This underlines again that BLI-capable concepts can only be achieved by using a **fully coupled, holistic design approach**. The previous and current separation of engine original equipment manufacturer (OEM) and airframe OEM will no longer be adequate if the potential of BLI is to be successfully leveraged.

On the other hand, new technologies such as electric propulsors offer more flexible propulsion system integration and handling during operation. Additional technologies like active and passive flow control can help to avoid or suppress unfavourable off-design operating conditions of a BLI propulsor.

2.4.3 Distributed Propulsion

The basic idea of distributing propulsors along the wingspan of an aircraft is to increase overall efficiency by either reducing the specific thrust through extension of the total propulsor area for an enhanced propulsion efficiency, or by increasing the generated lift of the entire wing. The latter effect strongly depends on the propeller arrangement and operating point. For a tractor configuration, the slipstream basically increases the local dynamic pressure and thus the lift, allowing for a smaller wing area, reduced structural weight and thus increased total aerodynamic efficiency. Lift gain, especially at low speed, has been proven by many tractor and also over-the-wing installation studies. Wing-tip-mounted propellers considered at the end of a distributed propulsion array along the wing offer special savings effects by overlaying and thus partially compensating for the wing-tip vortex with the propeller swirl. This leads to a partial recovery of the kinetic energy either in the tip vortices or in the swirl of the propeller slipstream. Additional effects to be considered at the system level are a reduction of the vertical stabilizer size due to reduced one-engine-off criticality as well as a reduction of high-lift device requirements due to the lift augmentation provided by the slipstream.

Distributed propulsion (DP) configurations have not yet been introduced, but preliminary studies show a potential reduction in shaft power via drag reduction of *10–20%*. This is, however, only applicable to the regional aircraft segment, since it requires a combination with electric machines and has to consider all associated constraints. Also, the benefit is influenced by the cruise speed, since propeller efficiency and wing drag in the slipstream are very sensitive to high local flow velocities. In the recent past, various configuration studies have been conducted to determine the dominant coupling effects between wing and propeller, and especially to derive the governing mechanism defining the optimal propeller configuration and position. For the spanwise direction, a uniform distribution of the propulsive power along the wing – with some distinct clearance between the propellers and towards the fuselage – is obviously in favourable. This has to be combined with the wing design to consider the non-uniform local angle-of-attack variation along the wing leading edge. However, for the axial gap and the vertical position relative to the wing, the interaction is much more complex. In particular, the streamtube of the propeller slipstream relative to the upper wing surface plays a predominant role in lift but also in drag behaviour. In addition, for all positions where the wing cuts the slipstream horizontally, the local swirl angle effect as well as the shift between the upper and lower slipstreams along the wing has to be fully understood and considered. On the other hand, a modified and DP-optimized propeller design that steps away from a more classic load distribution along the propeller radius towards a more uniform distribution can have a positive overall effect. This could even lead to concepts with reduced propeller peak efficiency for the isolated propeller but increased overall efficiency and robustness along the entire mission. But such a trade-off again defines the need for a sound and high-fidelity understanding and quantification of coupling effects as results of a fully coupled concept design and simultaneous optimization of the propeller and the wing.

Optimizing the DP-wing configuration requires careful definition of the cruise flight speed due to the fundamental drawback of higher local propeller inflow velocities for all propeller positions above the classic tractor configuration. This especially holds true for upper wing positions, where the lift increase is typically very high, but also the inflow velocity increases at the position of the propeller. This significantly reduces the ability of the system to achieve higher cruise Mach numbers at high overall efficiency. For all effective DP configurations and positions, the propellers have strong local interactions with the wing boundary layer or the high-lift devices, which typically leads to more aggressive stall behaviour in the wing, although at significantly higher lift coefficients. Also, for laminar or partial laminar wings, the local interaction causes periodic changes between laminar and turbulent flow on the wing plus additional cross-flow components where the propeller slipstream interacts with the wing, which all significantly affects flow separation phenomena. Close coupling of the propeller to the wing also introduces a highly unsteady local flow field, which acts as an additional noise source. In particular, rearward propeller positions near the trailing edge in domains with smaller ambient velocity increase aerodynamic efficiency – but also noise.

Very similar to the above-mentioned BLI challenges, considering only the propeller layout and arrangement is not sufficient for effective DP along the full operating range. Instead, the overall effectiveness depends on a synergistic design of propeller and wing geometry. For such design tasks, reduced order models are required that are able to describe the dominant coupling effects, although the unsteady aerodynamic phenomenon might be quite complex in its nature.

While technical solutions such as span-wise DP or wing tip propulsion have been conceived to a certain extent, their actual introduction to SMR and LR aircraft designs is not deemed viable due to the above-mentioned reasons, plus the sizing benefits of gas-turbine-based propulsors. Thus, DP will not be considered as an efficiency contributor at the aircraft level in *Chapter 3.2*.

2.4.4 Novel Engine Concepts

Gas turbine engines are an excellent choice for aircraft power plant systems. They feature high levels of thermal efficiency, are exceptionally lightweight for the multi-megawatt power requirements in commercial aviation and have proven to be extremely reliable. Their intrinsic power characteristics as a function of airspeed and altitude (thrust lapse) are optimally aligned with modern subsonic transport aircraft operations. However, gas turbine thermal efficiency is strongly size dependent and there is a trade-off between higher cycle efficiency and lower NO_x emissions. With turbo-component efficiency levels at or above *90%* and burner-exit temperature levels approaching stoichiometric combustion conditions, the realization of significant further improvements in the thermal efficiency of classic Joule / Brayton cycle-based gas turbine engines becomes increasingly challenging.

Revolutionary engine concepts may enable the necessary step changes in energy efficiency through an improved heat transfer to the thermodynamic process or through suitable techniques to harvest Joule / Brayton-cycle waste heat in the exhaust. The former means higher thermodynamically effective temperature and pressure levels, e.g. via pressure gain combustion (e.g. via pulse detonation, rotating detonation or piston-based combustion) or through the introduction of topping cycles that act as high-quality gas generators for the baseline gas turbine engine. In addition, cycle intercooling provides for reduced compressor work and lower burner-inlet temperatures per overall pressure ratio. The utilization of Joule / Brayton-cycle waste heat can be achieved via recuperation techniques (e.g. preheating of cryogenic fuels, precombustion heat transfer to the main working fluid, steam generation, secondary fluid recuperation, thermoelectric generation) or by introducing bottoming cycles (e.g. super-critical CO_2, open air expansion) that use the gas turbine exhaust heat as energy input.

Advanced composite cycle engines (CCE) – gas turbine power plants with piston-based gas generators – feature superb thermal efficiency due to cycle peak pressure ratios well above *100*. Low-TRL aircraft integrated assessments have shown robust fuel burn reduction potential over advanced GTF technology of *≥10%*. The key critical issue for CCE-type power plants is NO_x emissions. In addition, more lightweight piston engine components are required for keeping the power density at the familiar levels of gas turbine systems. Abatement options for CCE-related NO_x emissions include compression intercooling, advanced piston combustion technology and water / steam injection.

Water or steam injection in gas turbine engines has a significant impact on engine performance and NO_x production rates during combustion. The effects of steam injection in gas turbine combustion chambers are mainly twofold: Thermodynamically, the work capacity in the turbine section is enhanced by additional turbine mass flow due to the added water. This base effect is greatly augmented by a corresponding increase in the specific heat of the turbine working fluid, unlocking high double-digit gains in thermal efficiency, depending on the injected water-to-air ratio (WAR). The injected water acts as a thermal ballast to the combustion process, yielding reduced effective local temperatures in the burner and leading to significantly reduced NO_x concentrations in the combustion products. At *5%* WAR, NO_x is cut by half, while *10%* WAR would yield *80%* less NO_x. As one option, besides utilizing heavy water tanks, the product water mass flows of an onboard fuel cell system could be utilized.

Hydrogen fuel cells (H_2FC) enable the direct electrochemical conversion of ambient oxygen and hydrogen to pure water. Fuel cell efficiency is not subject to Carnot efficiency limits, but parasitic loads from the required auxiliary systems, referred to as the balance of plant, dilute the isolated efficiency measured at the fuel cell stack. In result, fuel cell system efficiency values are roughly in the same range as the thermal efficiency of medium-size gas turbines, with the scaling properties of gas turbines triggering efficiency advantages for fuel cells in small power classes up to typical regional turboprops. The maximum operating temperature limits of electrochemical conversion make fuel cells stacks – even high-temperature SOFCs – NO_x-emission-free systems. Compared to gas turbines and depending on the temperature at which the given fuel cell type is operated, thermal management and ambient heat rejection are major challenges. Hydrogen, however, can also be burned directly in gas turbine engines (H_2B). Here, the products of hydrogen combustion feature higher specific heat and isentropic exponents than those of kerosene or SAFs. The resultingly increased turbine work capacity leads to a reduced core engine size and – depending on the thrust class – to an improved thermal efficiency compared to drop-in fuels, on the order of *5%* for large turbofan engines. The utilization of hydrogen's intrinsically low lean blow-out limits for minimized NO_x production, however, remains a design challenge when considering all operational requirements for an aero engine combustion system.

H_2FC and gas turbine (GT) technology can be combined synergistically in **hybrid configurations**. Here, three levels of systemic integration can be distinguished: a simple discrete parallel system in which merely the H_2FC electric power output is utilized (*level 1*), a water-integrated system in which also the H_2FC product water is harvested in order to augment the GT performance and drastically reduce NO_x emissions (*level 2*), and a fully GT-cycle-integrated arrangement aiming at a full utilization of the H_2FC's thermal energy output (*level 3*). In all cases, the H_2FC electrical power output can be utilized meaningfully to serve various onboard customers. Depending on the H_2FC size, scenarios ranging from a mere supply of the vehicle's all-electric subsystems to a radical single-GT propulsion system seem conceivable. Applying the latest lab-scale-validated H_2FC technology, initial assessments for water-integrated H_2FC–GT hybrid systems yield promising results. For a typical twin-GT SMR application, high single-digit improvements in block fuel have been found, while cutting high-level NO_x by *60%*. Even more attractive for the SMR market segment could be a radical H_2FC–GT hybrid involving only a single gas turbine engine with approximately 50/50 power share between the H_2FC and the GT systems.

Escaping the efficiency limits of the Joule / Brayton cycle naturally comes with penalties in system weight and complexity that need to be monitored closely. Revolutionary heat engines such as the ultra-efficient CCEs still face challenges in NO_x emissions and in durability when compared to advanced conventional gas turbine engines. Fuel cells involve not only the stack of electrochemical conversion cells but also extensive auxiliary systems required to manage the operating conditions for the electrochemical process. This includes the conditioning of the reactants as well as electrical, thermal, structural and humidity control for the fuel cell stack. The involved system weight penalties will have to be further reduced decisively while mastering the overall design and operational complexity.

2.5 Aircraft Systems

Future energy-efficient aircraft will require drastic changes in aircraft aerodynamics, aircraft structure, flight control, power plant architecture and aircraft operations. Aircraft systems themselves are not the main source of energy savings potential, but the aircraft systems design will also be subject to drastic changes, as these systems must provide the functionalities required by the evolution in general aircraft design. Innovative aircraft systems are essential for the implementation of the master concepts for energy-efficient flying, as systems are the service providers for all required functionalities. Therefore, system evolution must always be aligned with the general aircraft architecture evolution, as the non-achievement of a functionality with the required reliability will be a blocking element for new features. Otherwise, system design is the critical path and show stopper for an economically valuable realization of the next generation of aircraft. For future sustainable aviation, it is mandatory to push the limits of conventional system approaches and to perform transformations leading to new vehicle system architectures with innovative technology bricks, e.g. in the areas of onboard power systems and efficient energy management. This poses complex multi-physics challenges not only for the interdependence between structure, propulsion and aerodynamics but also for energy storage and distribution, electrical architecture, thermal management, reliability and certification, as well as life cycle management. This chapter is dedicated to the potentials but also challenges for **future onboard systems to enable energy-efficient aircraft** with significantly reduced climate impact.

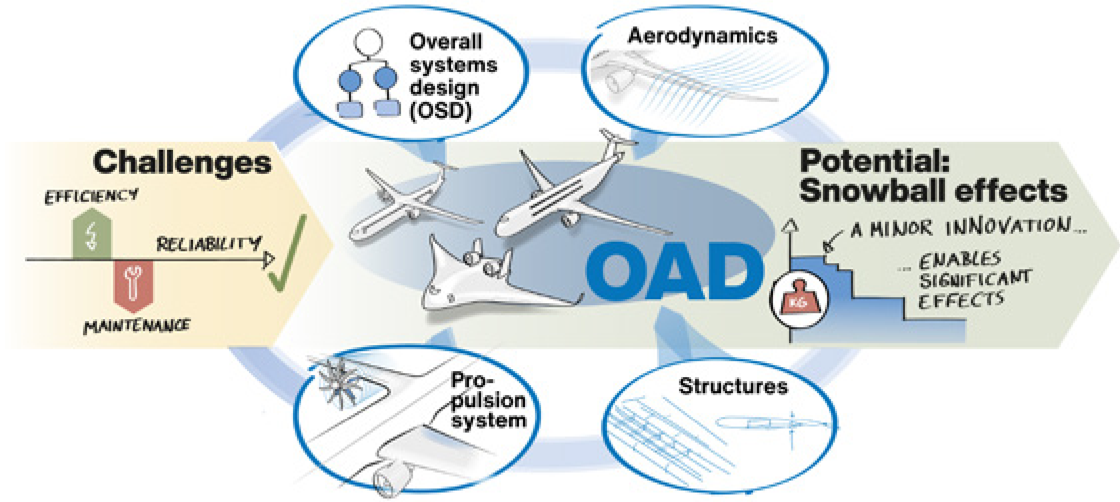

Figure 12: Future aircraft systems concepts require careful multi-disciplinary optimization, to ensure benefits maturing and positively snowballing at the overall aircraft level

2.5.1 Optimization of Onboard Power Systems

The master concept of **More Electric Aircraft (MEA)** is based on the optimization of conventional non-propulsive aircraft power and the stepwise replacement of pneumatic and hydraulic systems with electrically powered solutions. This has a strong impact on the secondary power architecture of the aircraft and requires new technology building blocks as well as innovative system components.

Successful implementations have been carried out, for example, for the Boeing 787 and the Airbus A380 and A350 aircraft. From a systems engineering perspective, it is important to understand that efficiency increases and weight savings are generally realized through new architectures, which, however, require new devices as a prerequisite. For example, the traditional integrated drive generator (IDG) including a complex constant speed drive has been replaced by new variable-frequency generators (VFG) directly connected to the engine gearbox. This reduces weight and maintenance costs. It is considered to be more reliable and allows additional functions such as the use of generators to start the engines. The use of engines without bleed air (bleedless) or with reduced bleed air (less-bleed) is leading to an efficiency gain by replacing pneumatic energy with electrical. However, electrically operated air conditioning, electrical ice protection and additional generator power are required for these concepts. Another important MEA example is the reduction of the hydraulic power distribution network. Hydraulic systems have been established in aircraft to supply consumers with high power density (flight controls, landing gear, brakes, etc.). The reliability requirements of the associated safety-critical functions have generally led to three independent power supply systems (*3H–2E*). Nevertheless, the introduction of new electrohydraulic actuators has made it possible to eliminate a complete supply circuit and ensure redundancy by connecting to the electrical grid (*2H–2E*).

Potential

The progressive goals of the MEA concept are to increase energy efficiency, improve reliability and reduce maintenance costs. There is a high potential to reduce operating costs, weight and fuel consumption by significantly improving engine efficiency and environmental compatibility. The elimination of the bleed air system allows further optimization of the core engine. Several system components such as pneumatic ducts, duct burst protection, valves, precoolers and over-temperature protection can be avoided. Since higher electrical loads with the bleedless MEA concept are the consequence, new generator networks and higher voltage levels (e.g. 540 VDC) could be implemented to reduce the required current and thus the cable weight. In this context, new power supply standards could open up a new design scope for the overall electrical power network architecture. Another forward-looking approach is the further decentralization of power supply systems in relation to different aircraft zones and consumers. New innovative concepts such as hydraulics-free engines without engine-driven pumps or zonal electrohydraulic power packages in the fuselage or tail can be considered. For cabin installations, the progressive decentralized electrical power distribution with secondary power distribution boxes and advanced structure integration concepts are promising. Overall, the MEA concepts have the potential to implicitly enhance the capabilities of advanced health monitoring, system diagnostics and prognostics to avoid aircraft-on-ground events (AOG) or unscheduled maintenance tasks.

Regarding the potential weight savings at the overall aircraft level, it is again evident that even new system solutions often do not lead directly to a significant weight reduction. Rather, it is the snowball effect that makes significant impacts possible by changing the boundary conditions or new architectures. For example, the development of a powerful digital sensor as a replacement for mechanical monitoring concepts only saves a few kg at the system level. However, the modified sensor characteristics and signal processing can reduce failure loads significantly and therefore have an indirect snowball impact on the structural weight.

Challenges

The More Electric Aircraft concept is essential and challenging for the implementation of future sustainable aviation. Due to the lack of aircraft development programs and the uncertainty of air transport concepts, too little effort is currently being made to consistently pursue the MEA path and achieve the necessary technological maturity up to higher technology readiness levels. Many things work in the laboratory. But some blind spots for the risks of industrialization seem to have developed in recent years. For example, there is still no operational solution for the electric actuation of the main landing gear or the electric steering on the nose landing gear for medium-size aircraft. It should be kept in mind that most of the potential improvements are associated with profound changes to the established system and safety concepts. These are not local modifications of the aircraft, but rather comprehensive and complex changes. New failure scenarios, common-cause failures and new types of complex fault-propagation mechanisms must be analysed very carefully. In the context of new technologies, new certification rules and corresponding means of compliance must be developed. In terms of industrial risk management, but also due to the physical constraints, there will be no quick option to implement an **All-Electric Aircraft (AEA)** for the next generation of civil commercial aircraft. The maturity and critical importance of the next-generation power electronics components must be highlighted. Robust high-power components play a critical key role, not only from a technical point of view but in terms of cost competitiveness in production and operation.

Synthesis

The main objective must be to improve the efficiency of aircraft systems while maintaining a good overall balance between mature technology, economics and the ecological aspects. Reliable technology modules with significantly higher power densities must be developed as a basis for the realization of new and optimized system architectures. Worldwide efforts to implement optimized onboard power systems in the field of electromobility also open new options in aviation. Important synergy effects can be used to accelerate developments. Particularly in the field of power electronics, major steps are necessary. New devices require higher reliability, technological maturity and an acceptable cost structure thanks to a broad industrial base in order to realize the concept of the More-Electric Aircraft to a greater extent. The development of new thermal architectures is also of outstanding importance, as bleedless and less-bleed concepts in particular set completely new boundary conditions for improved core engine design. Important development directions here are the improvement of the refrigerants in the systems, the design of thermodynamic cycle processes that take advantage of the degrees of design freedom gained, and the application of multi-phase cooling systems that have received little attention to date.

2.5.2 Systems for Active Control of HAR Wings

The systems enable control functions at the aircraft level, provide resources via the supply networks and handle safety-critical information from sensors and system failures. In this overall sense, aircraft systems are service providers and performance enablers. In the context of the pioneering aerodynamic concepts for drag reduction described in *Chapter 2.1*, the system components can be seen as enablers. This characteristic is often overlooked when focusing exclusively on the primary effective functions and is not included in holistic analyses. For the identification and evaluation of promising energy-efficient concepts and technologies, a multi-disciplinary approach is therefore imperative (see *Chapter 2.3*).

Potential

There is a high potential for **high aspect-ratio wings (HARW)** to reduce induced drag. Satisfactory handling qualities and operational aspects have to be considered in the context of multifunctional movables. New control-surface configurations with a hybridization of primary and secondary flight control surfaces have a high potential to improve the lift-to-drag ratio by controlling the wing shape and optimizing the wing performance. Significant structural weight reduction is identified through advanced load-monitoring functions and active load-control systems. Furthermore, the design of an integrated hybrid laminar flow control aircraft includes optimization of the aircraft configuration, aerofoils, redundant suction system, leading-edge high-lift device, lightweight suction structures and self-cleaning surfaces. Compared to conventional aircraft, the suction system is a completely new system that adds mass and power consumption and has an impact on the net benefit (fuel reduction) of the HLFC technology. The benefits on the aircraft mission level need to be carefully analysed to effectively exploit the huge potential of laminarization for future sustainable aircraft.

Challenges

The realization of high-aspect-ratio wings with new flight and load controls is associated with numerous systems-engineering challenges, which will be discussed in more detail here. First of all, the wing geometry and the thinner aerodynamic profiles significantly change the available installation space. The optimal integration of the actuation systems and the associated question of the thermal operating environment and the stiffness of the joints lead to new challenges.

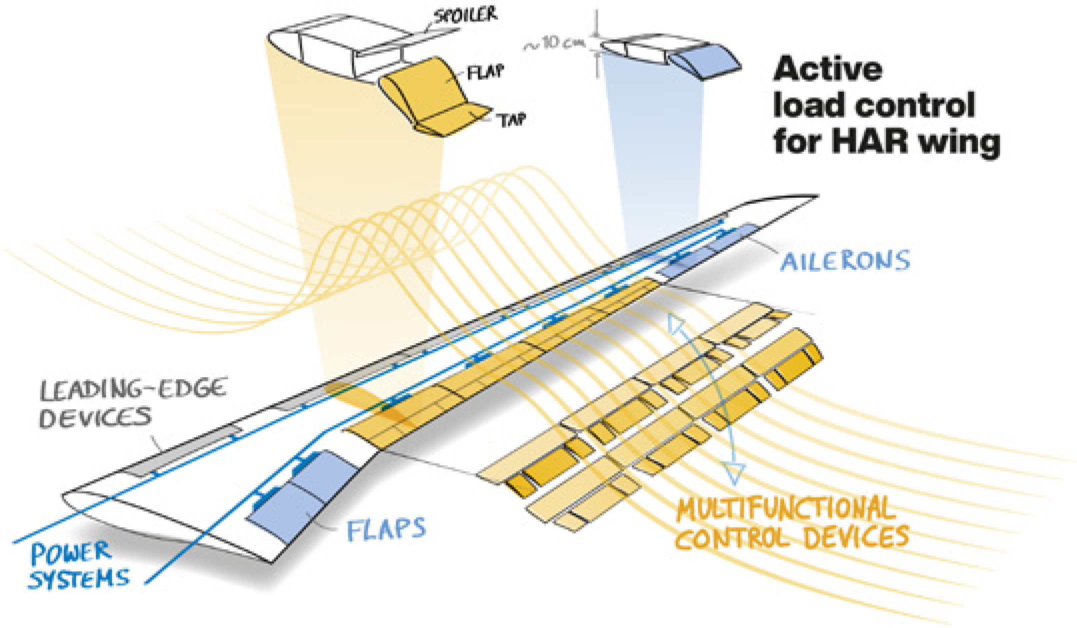

Figure 13: Advanced and reliably active load-control systems using multifunctional movables are mandatory to master the weight of high aspect-ratio wings

Today, the robust and proven hydraulic servo actuators (EHSA) are mainly used as actuators on the front line of the flight control system. They could be supplied by a modern electrohydraulic power package, allowing the fluid to be used to cool the actuators. If one consistently follows the concept of the More Electric Aircraft, one could strive to make the wings and the engine completely hydraulics-free (full-electric wing). This would require innovative electro-hydrostatic actuators (EHA) and electro-mechanical actuators (EMA) with high power density and local electronics. EHAs are already in use in the current Airbus A380, A350 and Boeing 787 aircraft – however, only as backup actuators that can take over if the primary EHSA fails. There are limits to the service life of the EHAs, as the operating cycles lead to premature wear and the thermal management of the EHAs is also limited. EMAs still have a lower degree of maturity, with few applications in primary flight control. Although they have very advantageous properties, they also have critical failure modes in practice. Linear actuators are typically based on screws, and these can jam due to mechanical faults. As this blocks the load path, the established system concepts of active–passive redundancy are not readily applicable.

Research solutions to this problem lead to complex components with jam-release devices, but also to further partitioning of control surfaces with active–active configurations. All in all, these are challenges that have not yet been fully overcome and that also result in system solutions with high procurement costs, weight and complexity. With new functionalities such as active load reduction and flutter control, the requirements for actuating speeds and dynamic profiles are also changing dramatically. Research projects have shown that optimal load reduction for HARWs requires very high actuating rates. This would require very large and heavy actuators with high electrical power requirements. In this context, so-called short-stroke damage to the actuator screws, which significantly reduces the service life of the system, is often overlooked. Therefore, the current status of actuation systems does not seem to meet the future requirements of an HARW, and accelerated efforts are needed to develop industrially viable solutions. An interesting interaction between the hydrogen aircraft under discussion and the wing also results from the intended storage of the liquid hydrogen in fuselage tanks. This results in a dry wing, where the weight of the fuel will no longer contribute to unloading the wing structure. In fact, the question is how the future system installation will look like with this degree of design freedom.

Synthesis

Considerable efforts must be made in systems engineering and technology to make the promising aerodynamic and structural improvements for a high aspect-ratio wing possible. Significant systems engineering and technology efforts are required to realize the promising aerodynamic and structural improvements for a high aspect ratio wing. Today, no mature actuation technology solution is yet available for the next generation of environmentally friendly aircraft. Joint efforts by flight physics, structure and systems engineering are required to master the challenges and overcome the recognizable show stoppers. Wings with very high aspect ratios and active load adaptation can only be realized with significantly higher power densities than those available today. All actuation systems for the wing with high aspect ratio and low-profile heights must be designed jointly and integrally. This is the only way to master the complex interactions between the aerodynamic loads, the optimal kinematics, the control surface size and function and the choice of an efficient actuator type. Local optimization, as was typical in the past, is no longer sufficient to find a solution. On the other hand, there is an urgent need for research and development into new, innovative component and device technologies. For example, motor types that have hardly been considered so far, such as axial flux machines, are of interest in order to reduce installation space, energy consumption and increase efficiency. New materials and manufacturing processes, e.g. 3D printing, must be included in order to ensure that service-life requirements are met with the significantly increased dynamic requirements.

New approaches must also be taken for the actuation systems on the leading edge of the wing, as studies have shown that the actuation forces required for torsion control when using a fast-moving droop nose, for example, are practically impossible to achieve. New solutions such as pop-up spoilers or active flow control systems with no moving parts need to be optimized and integrated into an overall concept. The advantages of fluid actuator systems, e.g. in conjunction with electro-hydraulic power packages, must be focused on. The modular design and the significant advantages of electro-hydraulic actuation concepts must be analysed holistically without being dogmatically restricted by guiding concepts. And of course, all innovations must yield the necessary reliability, otherwise the weight reductions cannot be realized, as the innovation will not be certifiable. Flight and load control are safety-critical functions that also require new redundancy concepts due to complex failure scenarios. The link to future signal-processing systems, new sensor systems with data integrity checks and a universal flight control platform (avionic system) must also be considered.

2.5.3 Onboard Systems for Hydrogen-Based Energy

New engine concepts based on hydrogen could open up a promising path to environmentally friendly aviation (see *Chapter 2.4*). Hydrogen combustion (H_2B) generates thrust by burning liquid hydrogen. This uses the same principle as kerosene gas turbines, but many system components are changed, like the combustion chamber, injectors, cryogenic heat exchangers and LH_2 pumps. Hydrogen fuel cells (H_2FC) are based on converting energy stored in LH_2 into electrical energy to power electric motors.

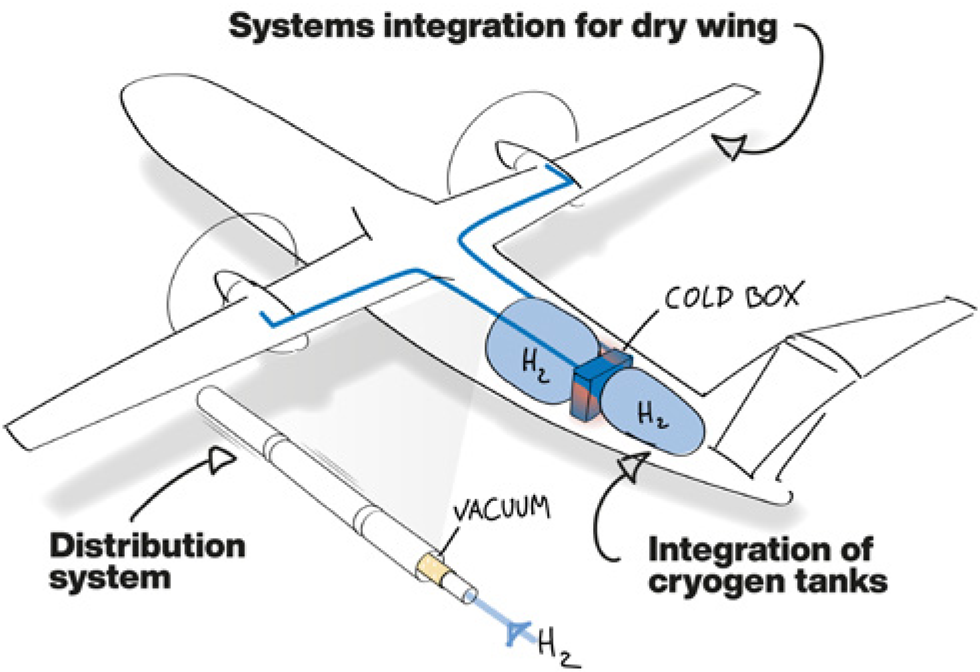

Figure 14: The integration of an LH2-based fuel cell system drastically changes the overall aircraft energy architecture concept

Combining H_2 gas turbine and H_2 fuel cells systems opens the design space for several hybridization strategies, but has a strong impact on the systems concepts also. On the one hand, there could be an electrical booster during take-off and climb, and on the other hand deeper integration of the systems may be beneficial. Fuel cells as a secondary power source and replacement of the APU are also used as enablers to increase gas turbine efficiency due to reduced power offtakes and fuel-cell-processed water usage. This section describes the potentials and challenges of LH_2-based concepts and their major impact on the systems.

Potential

Fuel cell systems are characterized by high environmental compatibility and efficiency. Compared to gas turbines, the conversion efficiency is around *60%*. Liquid-cooled low-temperature LT-PEMFCs have a high power density, a compact stack design is possible and adequate dynamic capabilities with fast startup and shutdown procedures are technically feasible. With respect to thermal management, the limited ΔT to environment on hot days and the water management require robust system solutions. High-temperature HT-PEMFCs have some advantages at the system level, since no additional liquid or evaporative cooling, no humidification systems and less filtering are needed (more resilient with respect to reactant pollution). However, at the stack level the state-of-the-art technology has a lower performance than LT-PEMFC, with more complex and time-demanding startup routines and a less mature technology level and not yet fully meeting the lifetime targets of aviation. But a lot of progress is possible and important potentials are identified. The non-propulsive concept of a multifunctional fuel cell system enables a wide range of innovations not only through the use of electrical power but also due to the use of the reaction product water and the oxygen-reduced exhaust air for tank inerting and fire protection in the cargo area as well as for use as an emergency energy source (RAT replacement). Such a fuel cell system can then also be used for emission-free ground operation. Another concept for decoupling electrical energy generation from the engine is decentralized electrical power packages such as the so-called fuel cell energy trolley in the galleys. This enables airline-specific adaptation to the energy supply for the cabin, and a modular system architecture with advantages in production, operation and maintenance is feasible. Increased power densities in the future could turn these approaches into an economically competitive industrialization.

Challenges

One of the most important and challenging questions is how to store H_2 in an aircraft. In general, H_2 is three times lighter than kerosene. However, for the same amount of energy representative of *1 litre* of kerosene, a volume of more than *3000 litres* of hydrogen at *1 bar*, *6 l* for pressurized H_2 at *700 bar*, and only *4 l* of liquid hydrogen are required. Cryogenic storage of the H_2 is seen as the best systems solution, and low temperatures at low pressure levels to increase LH_2 density are beneficial for LH_2 tank capacity. These requirements lead to tank systems with an inner and outer vessel containing a vacuum in between to prevent convective heat transfer. Also, a multi-layer insulation is added here to sustainably maintain the cryogenic temperatures in the inner tank. To enable LH_2 fuel supply and extraction by using the inner-tank heat exchanger (HX) for evaporation and to deliberately control tank pressure, the outer-tank HX regulates supply temperature and provides heated H_2 to the inner HX as well as multiple pressure relief routes for safety. Another challenge for liquid distribution systems is to ensure liquid H_2 extraction from the tank under all aircraft operating conditions, e.g. during *1 g*, *0 g* and *-1 g* load cases as well as with fuel dynamics (sloshing) at low fill levels. Further overall challenges are the high system complexity of fuel cell control (HW & SW), air supply, cooling loop, hydrogen recirculation, humidity and monitoring systems. All studies show that hydrogen-based solutions pose major challenges in terms of aircraft configuration, system weight, reliability and also economic costs.

Synthesis

The main challenges of H_2 transformation are bringing the weight and cost down, mature technologies, finding international agreements on regulatory standardization (technology and rules) and making available a robust LH_2 infrastructure with a step-by-step transition and long-term plan for the growth of the renewable electricity and hydrogen ecosystems. Significant development efforts are required in order to develop a competitive H_2- and fuel-cell-powered aircraft. Nevertheless, the use of green hydrogen for the engines, but also for the onboard energy supply, has by far the greatest advantages for sustainable future aviation. Certification and the means of compliance with FAA / EASA rules are key elements for this path.

3. Configuration, Design and Development

3.1 Configurations

A configuration always resembles the best compromise in bringing a variety of technology bricks together in order to get the **most competitive aircraft** (economically as well as ecologically). Thus, new technology options always challenge the status quo of the classic tube and wing configuration.

What may be the driver now to evolve to other aircraft designs? The significant increase in awareness with regard to the climate impact of aviation nowadays puts emission reduction priority one as a design target. While in the past the economic superiority of a new design has been top priority from an operator's point of view, the economics will change. As the key element for emission reduction will be a sustainable energy carrier, the cost for energy is likely to double or even triple in the future. This will allow higher investments in aircraft technologies, i.e. higher aircraft prices, if they "pay off" by reducing climate impact and also direct operating costs (DOC). Thus, more radical technologies might be introduced or even previously disregarded ones revisited in order to achieve the "new economic efficiency".

In the following chapters the elements of such beneficial compromises will be addressed for the evolution of kerosene-based aircraft concepts and then for hydrogen-based designs, and finally changes in the operations and operational-respective infrastructural constraints will be addressed.

3.1.1 Kerosene- / SAF-Based Configurations

Introduction

The use of kerosene as an energy carrier has been the basis for more than eight decades of aircraft design and enhancements. With different pathways to sustainable aviation fuel being available, in particular CO_2 reductions of *>85%* seem feasible. Sustainable Aviation Fuels benefit from the positive fuel properties from an aircraft design perspective. Compared to hydrogen, for example, the load-relieving benefit in wing storage remains valid, such that further improvements in propulsive, aerodynamic and structural efficiency are expected.

Thus, candidate technologies for these aircraft are:

- High aspect-ratio wings
- Open rotor / ultra-high bypass ration engines (UHBR – BPR ~ *18*)

- Viscous drag reduction (e.g. laminar flow, BLI)
- Passive and active aeroelastic tailoring
- Load alleviation
- Weight reduction through structure technologies

Potential

These technologies will show varying impacts on the vehicular efficiency (total energy efficiency) depending on the configuration they are applied to. In this segment the most promising options are represented by:

- advanced tube and wing
- advanced tube and wing featuring a forward-swept laminar wing
- strut-braced wing configuration
- blended (wing) body configurations / flying wings

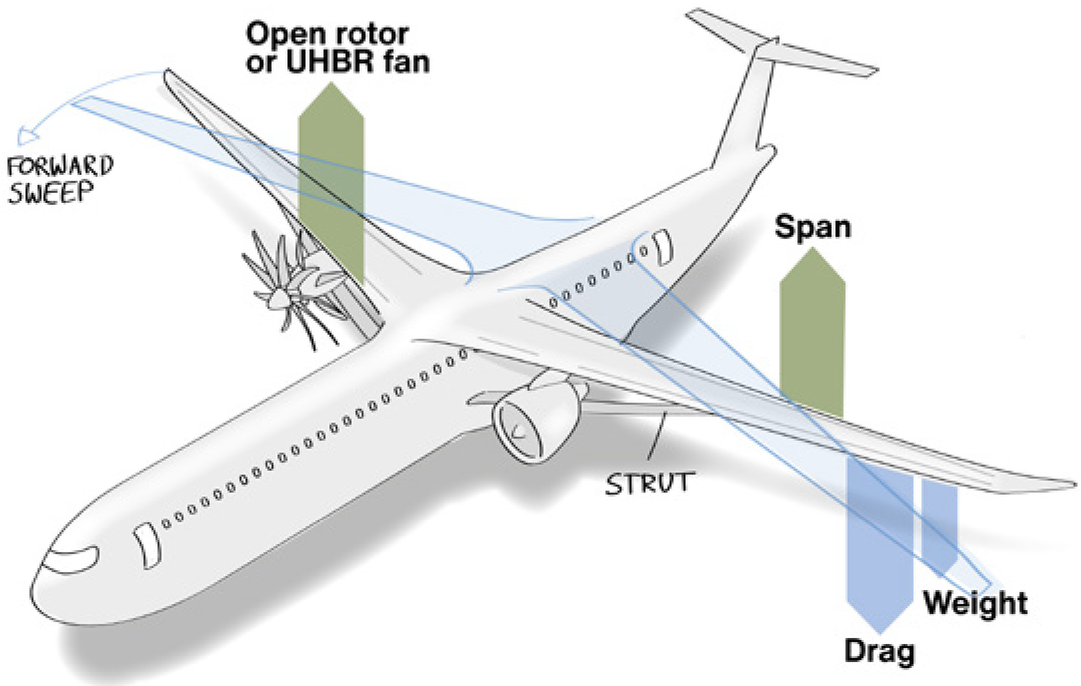

Figure 15: Integration of advanced technologies may result in significant overall aircraft configuration changes

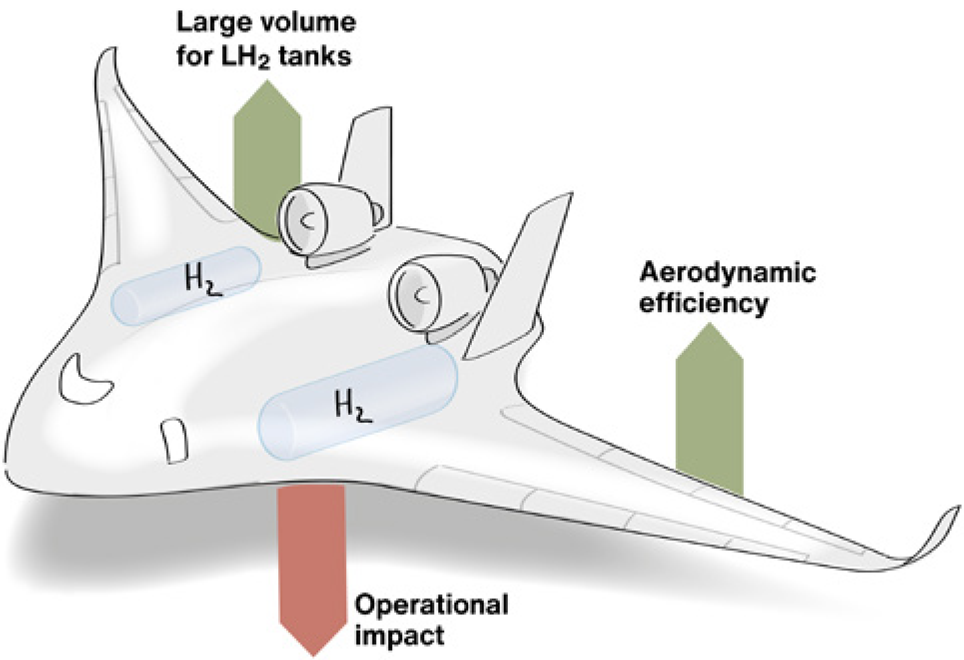

Figure 16: Disruptive aircraft configurations may offer the required novel degrees of freedom for the integration of advanced technologies

The **tube and wing configurations** rely on the widest experience in design, production and operation. Further enhancements are considered feasible through higher aspect-ratio wings, higher BPR engines, higher structural efficiency and measures to reduce the viscous drag of the configuration. The latter may, in combination with a forward-swept wing, even achieve natural laminar flow on the wing to a very high degree. Taking an isolated view of the contributions of the individual technologies, this might lead to possible reductions in fuel burn of up to *50%* (see *Chapter 3.2*) compared to current state-of-the-art aircraft designs.

The **strut-braced wing configurations** provide two major advantages over the conventional tube and cantilever wing, as this layout reduces the structural loads of the high-AR wing, while enabling at the same time, due to the high wing design, the integration of higher-BPR propulsion systems in the favourable podded engine integration. Without considering detrimental effects, the additional gain in fuel burn reduction may be on the order of *5%*, as all other technologies might be applied as well to this type of aircraft.

In **blended (wing) body design**, the blending of the fuselage into an “active” aerodynamic body with a higher aerodynamic efficiency may lead to higher aerodynamic efficiencies, achieved through less viscous drag, a higher effective span leading to improved induced drag and the lift performance of such configurations. Taking an isolated perspective on this aspect, this might promise a further increase in vehicular efficiency, which in reality, due to high interaction effects, will not materialize to the full extent.

Challenges

The **tube and wing configuration** features a couple of challenges, making it hard for this mature design to fully utilize the potentials of the technologies addressed. The increase in aspect ratio will only be possible by introducing folding wing-tip mechanisms, which will have an impact on empty weight and system complexity. Advanced aeroelastic tailoring, including reduced certification limits on loads, in combination with high-strain materials and novel CFRP design principles may offset the structural weight increases driven by the higher aspect ratio, but will most likely not allow further weight reductions on the wing. The low wing configuration will put limitations on engine integration for UHBR engines or, even worse, an open rotor design at current wing positions. Thus, propulsive efficiency gains will be partly offset by integration effects and increased structure and system weights (a.o. landing gear or fuselage). While the highest gain would be achieved with laminar flow on the wing or even on the fuselage, this also comes with implications at the aircraft level. While a forward-swept wing will show good aerodynamic performance at cruise, the performance at low speed may suffer, due to lower efficiencies for the high-lift devices. Taking these integration effects into account, a fuel burn reduction potential of around *40%* may be expected.

While the **strut-braced wing** does show clear benefits on structural integration of the high-AR wing and UHBR integration, this configuration also comes with some challenges. Due to the strut, higher viscous and especially pressure drag are to be considered on the strut and the strut / wing interface. Integration on a highly swept, high-AR wing may in addition lead to further aeroelastic loads that need to be compensated for. While this might be achieved with advanced aeroelastic tailoring systems, the active load-alleviation potential is limited to the outer wing segment only. Finally, the high wing configuration will most probably lead to a T-tail with increased vertical tail size, as well as body landing gear that results in higher structural fuselage and system masses. Due to these effects it is considered that the strut-braced wing configuration will most likely not outperform the advanced tube and wing configuration.

The **blended (wing) body** or flying wing configuration has been around for decades due to its favourable aerodynamic potentials. All other aspects, though, suffer with this type of configuration: the pressurized cabin in a non-cylindrical shape will result in a complex and heavy structure; engine integration is mainly possible on the upper “fuselage”, leading to lower propulsive efficiencies; and even AoA limitations are conceivable. Although frequently addressed in these configurations, boundary layer ingestion will not be beneficial with this type of configuration, but rather will alter fan efficiency due to distortion effects. The position of the centre of gravity will lead to wing fuel tanks not being completely usable, in order to maintain a positive static stability in all operational conditions.

While the aerodynamics might be very beneficial in cruise conditions, the low-speed performance will be scrutinized due to the no-tail configuration and the resulting limited high-lift performance. This might lead to operational and capacity impacts at airports. Finally, the massively increased volume due to the blending of the fuselage may not be efficiently used and will lead to dead volume and weight. Given all these effects, it is considered that despite the expected better aerodynamic performance, the blended (wing) body will fall short against the tube and wing, with an expected fuel saving of around *30%* in this scenario. One overarching limitation is valid for all blended (wing) body designs: the increased “fuselage” width will result in a significant increase in span, which makes it almost impossible (without massive wing-folding systems) for all sizes of BWBs (SMR and LR) to fit into the actual airport size classes.

Synthesis

Although the potentials of an advanced tube and wing configuration may seem limited at first sight, they might still show significant reduction potential, if good solutions are found for an efficient integration of UHBR or open rotor engines, probably along with measures to reduce the viscous drag. This may be achieved through a propulsive fuselage design (BLI fan) or laminar flow control on wing and fuselage. While the BLI system will be mainly beneficial on longer ranges, laminar flow techniques would be beneficial for SMR and LR aircraft.

The strut-braced wing configuration could be a viable alternative for the tube and wing configuration, if no beneficial engine integration options are found. The full aerodynamic and structural potentials still need to be demonstrated, but further activities should be pursued in this field in Europe.

Blended (wing) body designs are not considered favourable in a kerosene / SAF scenario for a next-generation aircraft type, due to the limited potentials in combination with massive technological risks at hand.

3.1.2 Hydrogen-Based Configurations

Introduction

Hydrogen as the primary energy carrier for an aircraft will result in zero CO_2 emissions during flight as well as drastically reduced NO_x emissions, while the amount of water vapor will increase. If the effect of aviation-induced cloudiness can be limited for such a configuration, a massive reduction in climate impact is possible. The latter may require local adoptions of flight operations in order to avoid contrails, or technologies to reduce condensation of the water vapor.

The introduction of hydrogen as the primary energy carrier on board the aircraft will result in one massive configurational change: energy storage has to shift to the fuselage. In combination with the low volumetric energy density of hydrogen, even when taking liquid hydrogen (LH_2) as the best (and only viable) option for aircraft integration, some key configurational changes apply:

- significant increase in the fuselage volume
- significant increase in fuselage length, if a single deck is further pursued on a tube and wing configuration
- dry wings
- increased operational empty weight (OEW) due to insulated hydrogen tanks

At the same time, the usage of hydrogen also provides some benefits that may be utilized at the system or aircraft level:

- cooling capability of LH_2 (engines, electric motors and devices, etc.)
- reduced fuel weight

To leverage the benefits of using hydrogen, it becomes mandatory to introduce technologies that might be able to offset the detrimental effects of the hydrogen integration. Configurations of interest are tube and wing designs (with or without strut-braced wings) and blended (wing) body designs.

Potential

The introduction of hydrogen tanks on **tube and wing configurations** allows two possible options: front / aft of the fuselage, filling the full cross-section with spherical or conical tanks, and/or the placement of cylindrical tanks on top of the cabin, increasing the height of the fuselage. The first option will lead to an increase in the fuselage length if the cabin layout is not changed (single to twin aisle, double-deck configuration). These measures will limit the increase in length but will lead to bigger diameters for the fuselage, which is beneficial with respect to tank efficiency as well as the structural weight of the fuselage. The dry wing will lead to higher structural weight for the wing but may also create benefits, such as novel actuator integrations for high-AR wings, which are characterized by lower thickness and thus installation space for more powerful actuators, enabling active load-alleviation systems. Thus, a significant share of the wing structural increase may be offset by this.

One general characteristic element of hydrogen aircraft is the higher operational empty weight, due to tank, hydrogen system and surplus structural weight, while at the same time the fuel weight is significantly lower compared to a kerosene aircraft. The reduction potential for MTOW will get bigger the larger the aircraft and the longer the range. This will lead to reduced wing loading at take-off, climb and probably cruise, but increased wing loading during landing. As a consequence, the design points for low and high speed are closer together, relaxing the performance requirements for high-lift systems.

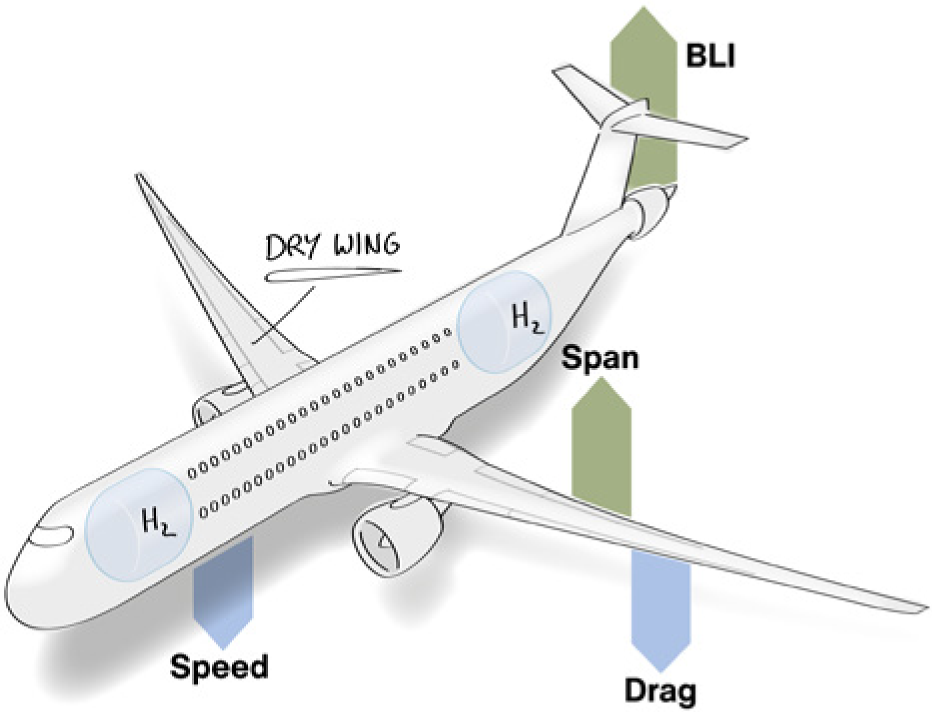

Figure 17: Hydrogen-based propulsion systems may break the inherited overall functional arrangement in the aircraft configuration

Blended (wing) body designs, due to their high internal volume at the blended wing root, will offer a good opportunity for the integration of cylindrical hydrogen tanks. Thus, no major outer shape changes are to be expected, resulting in very limited viscous drag penalties. At the same time the tank positions help to bring the fuel weight much closer to the centre of gravity compared to the kerosene version, leading to better trim characteristics and increased operational flexibility.

Challenges

The introduction of hydrogen as the primary energy carrier on board the aircraft will lead to new (re-)fuelling systems, insulated tanks, novel venting and safety systems, etc., which are currently still in technology maturation and where an agreed certification baseline with the authorities is still missing. How to comply with the safety requirements in aviation is still not completely clear, be it on the supply side of the hydrogen or the handling of liquid and gaseous hydrogen on board the aircraft. This is the case for all hydrogen-based designs and will pose significant challenges on testing and demonstration before the insertion into a product.

The increased size of the fuselage for a tube and wing configuration housing hydrogen tanks in addition to the cabin will lead to increased structural weight and a significant increase in viscous drag, which poses performance penalties to the aircraft. For shorter-range aircraft concepts, the placement of the tanks (minimum two, due to redundancy aspects) in the aft of the fuselage will have severe CoG implications, limiting the payload / range flexibility of these designs. The increase in the viscous drag might be partly offset by drag-reduction measures like a BLI fan at the aft of the fuselage. Due to the fuselage's higher drag share, this technology is likely to show higher benefits than on a kerosene aircraft.

With respect to the optimum design point, this might also help in balancing between induced drag benefits vs zero-lift drag penalties in the hydrogen design. While the higher wing loading in the landing configuration would be considered a performance penalty, it is not considered crucial for the time being, though this might depend on its final influence on the runway capacity for arrivals.

The blended (wing) body designs will still encounter the same challenges as for a kerosene-based configuration, except for the relaxation of the CoG issue in these designs. Still, the increase in wingspan will pose severe limitations, if current standards need to be applied.

Synthesis

While the tube and wing configurations in particular will face substantial design changes through the integration of hydrogen systems on the aircraft, the utilization of technologies on drag reduction, load alleviation and structural design as outlined in *Chapter 2* may be able to offset the resulting penalties. Thus, similar energy consumption may be realized as with an evolutionary kerosene aircraft design.

Blended (wing) body designs show a higher gain in the utilization of hydrogen, as the overall penalties of the configuration itself may be relieved. Detailed investigations on these configurations are still pending, such that a final assessment is yet to be made.

3.1.3 Operationally (Un-)Constrained Aircraft Designs

Introduction

The current air transportation system has evolved over the last eight decades along the standards defined by ICAO in the 1940s. This has led to quite narrow design spaces when it comes to cruise speed, approach speeds and finally the wingspan of current designs.

Due to the increase in demand for air travel over the last few decades, aircraft have been growing in size in order to compensate for this growth, as there are limitations in the total number of flights to be handled on the ground and in the air. This has led to a situation where currently all aircraft classes are severely constrained by these standards.

One aspect is the **geometrical constraint**, which mainly limits the wingspan to classes in the Aerodrome Reference Code (ARC). This is based on the fact that airports have planned and built their infrastructure in accordance with their expected fleet mix and the ICAO standards.

The second aspect, **flight speed** at cruise and low-speed operations, is driven by the maximum efficiency of the air transport management system, including the capacity maximization of the runway systems, which is a crucial capacity constraint for the performance of the overall air transport system. Reductions in flight speed, while favourable with respect to the fuel / energy consumption of the aircraft, would have a detrimental effect on airspace and runway capacity. They may even lead to higher investment costs for airlines, as significant increases in block time will result either in lower frequencies of flights or more aircraft to be employed to maintain the frequencies (cf. *Chapter 4.1*).

Potential

The increase in wingspan is the key enabler for high-AR wing designs and thus mandatory to further boost the aerodynamic efficiency of future airframes. While currently technologies such as wing-folding systems are employed to work around the existing limitations, these systems add weight and complexity to the aircraft, partly reducing the benefits of the wingspan increase. The elimination of the current span limitations would therefore make a direct contribution to the climate impact at the aircraft level.

Reduction of the flight speed is a well-known and quite efficient measure to reduce the fuel / energy consumption of an aircraft (cf. *Chapter 4.1*).

Challenges

Elimination of the ICAO ARC standards would shift some of the problems to the airport, as they might need to adapt the airport infrastructure to the new geometrical properties of future aircraft. To some extent this will be the case anyway, as further growth will also imply stronger utilization of larger aircraft over shorter distances, which will change the fleet mix at major airports in the mid / long term. Thus, the question may be raised if a rework / elimination of these limits should be seriously considered in order to enable further improvements to future aircraft types.

As already indicated, changes in flight speed, i.e. reductions in cruise speed and increases in approach speeds, will have a direct impact on airline operations and the capacity of the system. While the block time reductions for short ranges might be considered negligible from a passenger perspective, one would consider the impact on long range more severe, as it could lead to increases of flight times *>1 hour*. Still, looking at the flight behaviour of travellers, it becomes obvious that only *32%* of all long-distance trips are via non-stop flights. The time penalty from reduced cruise speeds could easily be more than compensated for by offering more direct flights, which show a smaller environmental footprint anyhow.

Synthesis

The elimination of existing operational and infrastructural limitations shows a very high impact on the performance and thus energy efficiency of future aircraft concepts. Utilizing these potentials can unfold saving potentials of around *10–20%* of energy consumption. This is well beyond the current optimizations addressed in a further evolution of the air traffic management system. Nevertheless, this will be accompanied by a restructuring of the air transport system as a whole in order to enable these long-term potentials.

3.2 Efficiency at the Aircraft Level

Introduction

This document focuses on energy efficiency in transport aircraft, and technological pathways for airframe technologies as well as for new aircraft configurations have been outlined targeting a reduction of energy consumption by *50%* or more. However, it should be noted that the potential for efficiency increase through applying an individual technology ultimately depends on the specific aircraft class (regional, medium- or long-haul / propeller or jet / high subsonic or transonic / classic or new configuration), i.e. concrete values for improvements require a specific analysis of the different technologies on a case-by-case basis, both individually and in their interaction. Furthermore, reliable overall improvement gains can only be established on the basis of a specific, thoroughly designed aircraft configuration. These caveats should always be clearly kept in mind when considering estimates of what **efficiency improvements** can be achieved with the technologies addressed in this document.

With these precautions noted, in the following an estimate of the possible efficiency improvement through applying the technologies in *Chapter 2* will be given at the aircraft level.

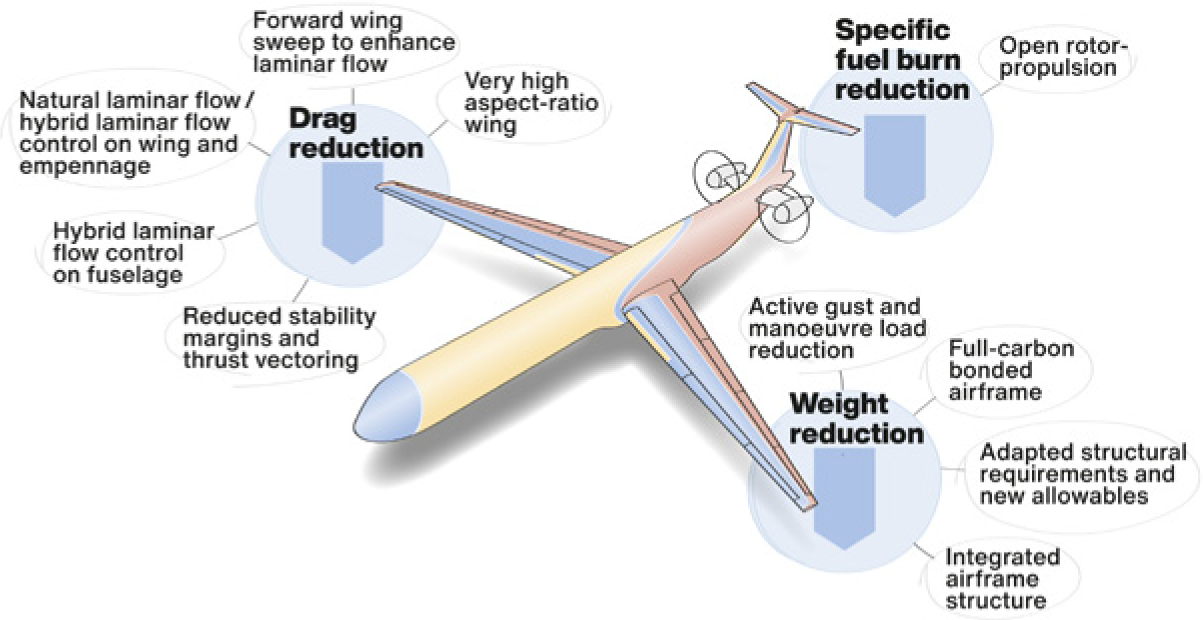

Figure 18: Identified key contributors to energy efficiency at the overall aircraft level

Potential

The potential for increasing energy efficiency will be sketched for a novel short- and medium-range (SMR) aircraft configuration flying at about *M ~0.78*. This cruise speed reflects today's TLARs (top-level aircraft requirements) for SMR aircraft, to allow a rigorous assessment of the applied technologies. The technologies described in this document will be applied in an idealistic way to maximize energy-efficiency gains, i.e. no constraints arising from operational and/or market conditions will be taken into account. The premise is to define the technological envelope for achieving ultimate energy efficiency, not to outline the next product from any manufacturer. The low drag configuration from *Chapter 2.1* will be used as a basis to estimate the potentials of novel energy-efficient technologies. Thus, the corresponding demonstrator aircraft is based on the layout of a forward swept-wing configuration with an aft-mounted open-rotor propulsion concept using preliminary aircraft design data.

In the following table, the specific technologies applied to the demonstrator configuration are given in the first column, the second column shows an estimate of their maximum net benefit for fuel consumption (and if applicable for empty mass), in the fourth column this maximum benefit is subjected to an uncertainty margin, and the last column contains comments on the margins. All gains in energy efficiency are given relative to the A350 technology status.

In the these estimations, it is assumed that the primary aircraft structure represents about *50%* of OWE (Operational Weight Empty). Applying technologies such as laminarization on wing and empennage, new materials, load reduction, reduced stability and open rotors, a maximum fuel burn reduction of *52%* may be achievable, or a *40%* fuel burn reduction when the uncertainty margins are included. Combining all technologies, i.e. also realizing a windowless fuselage with HLFC on the fuselage, the potential will add up to a maximum effect of *-60%* on fuel consumption, and *-46%* when including the uncertainty margins.

An overall effect of resizing the aircraft to fulfil a prescribed mission can be expected in addition (snowball effect). This will reduce wing area by *10–15%* and MTOW by *8–12%*, leading to a further reduction of fuel burn on the order of *5%*.

Technology	Net benefit	Technology reduction factor	With margin on net benefit	Technology reduction factor	Comments
NLF on FSW wing	Fuel **-17%**	**0.83**	Fuel **-12%**	**0.88**	Including favourable effect on wing AR and resizing. Margin for possible wing and fuselage weight increase and empennage surface increase for forward-swept wing.
HLFC on empennage	Fuel **-2%**	**0.98**	Fuel **-1%**	**0.99**	Reduction due to suction requirements.
Carbon airframe fully bonded (CAFB)	Primary structure -28%; Empty mass -14%; Fuel **-11%**	**0.89**	Fuel **-8%**	**0.92**	Margin due to limited application potential on aircraft.
Adapted requirements: 6000 microstrain, new allowables	Primary structure -17%; Empty mass -8%; Fuel **-6%**	**0.94**	Fuel **-4%**	**0.96**	Margin due to long validation efforts.
Integrated airframe structure	Empty mass -5%; Fuel **-4%**	**0.96**	Fuel **-3%**	**0.97**	Margin due to limited application potential on aircraft.
Gust and manoeuvre load reduction, 1.67 g	Empty mass 12%; Fuel **-10%**	**0.90**	Fuel **-6%**	**0.94**	Margin due to immature actuation technology.
Reduced A/C stability and use of thrust vectoring	Fuel **-4%**	**0.96**	Fuel **-3%**	**0.97**	Assumes up to 50% reduction of empennage is possible. Margin due to risk of system weight growth.
Propulsive efficiency of open rotors	Fuel **-15%**	**0.85**	Fuel **-12%**	**0.88**	Margins for risk on weight increase and noise mitigation.
Total benefit (without HLFC fuselage)	***Fuel -52%***	*0.48*	***Fuel -40%***	*0.60*	*Total reduction factor (result of multiplying all individual technology reduction factors).*
HLFC on fuselage of A/C with FSW	Fuel **-17%**	**0.83**	Fuel **-10%**	**0.90**	Including favourable effect on wing redesign and A/C resizing. Including suction pump drag. Margin due to immature technology: weight increase due to structure and systems.
Total benefit (with HLFC fuselage)	***Fuel -60%***	*0.40*	***Fuel -46%***	*0.54*	*Total reduction factor from multiplication with reduction factor of HLFC technology on fuselage.*

Challenges

Technologies can never be regarded in isolation, i.e. the potential of a particular technology identified under laboratory conditions is not representative when applied on an aircraft. Therefore, simply adding up technology potentials to conclude what can be achieved at the aircraft level is unrealistic. On the one hand, technologies will always interact when applied in combination, and it is by no means guaranteed that they will interact favourably with each other. Second, when a technology is integrated into an aircraft, it may not be feasible to leverage the full potential of that particular technology, since compromises may need to be made with respect to weight, volume, system requirements, certification restrictions, etc. Thus, the combined potential for energy efficiency given in the table above has to be regarded as the realistic maximum when the margins listed in the table are included.

Synthesis

The combined effect of summing up all energy-efficient technologies shows a maximum efficiency increase of more than *50%*, where snowball effects from resizing the aircraft are not yet taken into account. However, when integrating all these technologies into an aircraft, the eventual energy efficiency will certainly be lower than the theoretical maximum. It is also obvious that, whatever the final potential will be, this cannot be leveraged in one single step. Therefore, the final potential has to be approached in successive steps as part of a continuous development effort. In this continuous development effort, the different technologies have to be matured towards applicability, and depending on their actual status they can be integrated into an actual product. Consequently, some technologies will reach product maturity earlier than others, and operational experience will be gained. Based on this operational experience, the necessary compromises when integrating further, more future technologies will be easier to make, and the corresponding risks will be mitigated. It may even be envisaged that these experiences can facilitate the integration of new technologies due to unexpected synergy potentials. Also, it should be kept in mind that the time perspective for product maturation of several technologies addressed in this document is on the order of two to three decades. Implementation into an aircraft should therefore not be judged by the technology level of today, but overall progress in, e.g., materials, manufacturing processes, automation and autonomy and information technologies in general should be anticipated.

It should be clearly noted that in this example the design cruise speed was retained at today's high level of $M=0.78$. The table above shows that even for this high cruise speed, fuel savings of *50%* or higher are achievable. When energy prices and emission reduction become the primary design drivers, one may be forced to reduce this high cruise speed despite the corresponding reduction in transport performance. A reduction in cruise speed will have a significant impact on the appropriate propulsion system (e.g. propeller instead of open rotor) and wing sweep. This will enable additional fuel savings on the order of *10–15%* (cf. *Chapter 4.1*).

3.3 Multi-Disciplinary Optimization (MDO)

Introduction

The overall goal for civil aviation is to develop sustainable aviation, in particular comprised of aircraft with less or even zero climate impact. New propulsion concepts such as electric / hybrid-electric distributed propulsion, hydrogen-based propulsion systems, and the use of SAF offer the potential to minimize fuel-related emissions and noise. Yet it is not clear whether and which of the currently discussed concepts will find their way into viable products, since the tremendous complexity of modern transport aircraft is associated with high risks during their development, including production and testing. A "virtual product" strategy with the thorough virtualization of all design items, development, production and aircraft operation processes bears the potential to master the challenge of combining environmental sustainability with economic success and competitiveness. All associated aircraft disciplines, such as aerodynamics, structures, propulsion, flight control, aeroacoustics, etc., and ideally all production aspects need to be fully virtualized by means of **digital-simulation model-based engineering (MBE)** and **product data management (PDM) processes**. In a corresponding virtual-product engineering environment, all aircraft design disciplines and their associated design processes have to act closely together to enable fast iteration, assessment and optimization of new concepts with respect to the requirements extracted from the overall aircraft life cycle. As a consequence, future design, engineering, production and management processes will reflect these multi-disciplinary aspects from the very beginning, where all involved disciplines are represented in an adequate, problem-oriented and physically fully reliable manner.

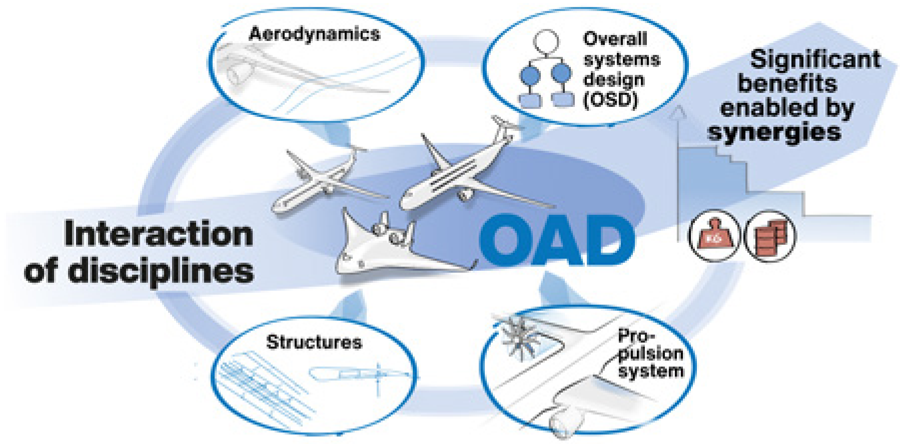

Figure 19: Multi-disciplinary aircraft design and integration needs to ensure synergetic combination of the efficiency technology building blocks

Potential

In industrial aircraft design, technological decisions have to be made very early in the design process, resulting in severe consequences when design modifications become necessary in the later phases of aircraft development. Therefore, numerical simulation has become an indispensable element of the design process, and multi-physics / multi-disciplinary analysis has emerged as a key enabler. In a numerically driven design and development process, where all relevant aspects of aircraft development are represented in sufficient detail, conflicts and necessary compromises will appear right from the initial stages of the definition phase. Additionally, with a validated and reliable simulation process, certification considerations can be supported in the early phases of the aircraft definition, leading to substantially reducing risk and cost.

Multi-disciplinary numerical simulation has evolved to be one of the most important future technologies. It is employed for product design and improvement in all relevant industrial high-technology sectors. Using high-fidelity, physics-based methods, numerical simulation holds promise to achieve realistic multi-disciplinary analysis (MDA) and optimization (MDO) capabilities for total virtual-product validation, verification and optimization. This may significantly cut down development and production time, risk and cost for future design and production processes, provided that manufacturing capabilities are also taken into account in this early phase. In conjunction with increasingly powerful high-performance computing (HPC) capabilities, a comprehensive virtual-product environment might be set up through employment of high-fidelity numerical simulation. This will lead to tremendous benefits for future product design and production processes, such as virtual design and virtual flight testing, as well as progressively moving towards virtual certification, namely Certification and Qualification by Analysis (CQbA).

Such a platform is mandatory to achieve the optimal combination of technologies for future sustainable aircraft, especially for unconventional, radical technologies and concepts where neither experience nor proven legacy data are available.

Challenges

The complexity of modern transport aircraft combined with the high level of maturity of in-service products leads to extremely high risks for the development and introduction of new concepts. In particular the introduction of new and/or unconventional technologies faces very high obstacles: setbacks with regard to cost or time have the potential to severely threaten even the existence of Original Equipment Manufacturers (OEMs) and their suppliers. However, to enable aircraft with substantially lower or even zero impact on climate, novel propulsion technologies like hybrid-electric concepts, potentially driven by hydrogen, appear promising, but the integration of such technologies has to deliberately consider their consequences for the configuration itself. This holds for conventional wing and tube configurations and to a much more extreme extent for unconventional configurations with distributed propulsion and/or boundary layer ingestion, or for completely new configurations such as blended (wing) bodies or flying wings. Only profound technological knowledge will make it possible to master the contradicting design requirements when integrating novel, sustainability-enhancing technologies into overall aircraft design. For the development, production and operation of "radically new and unconventional aircraft concepts" there are two main challenges to be overcome:

- Future design and engineering activities cannot rely on past experience from legacy configurations in terms of proven practices, parameterisations and scales; thus, one cannot refer to proven reference concepts, nor to proven design data and scaling parameters.

- To compensate for this lack of knowledge, an engineering environment very closely coupled with self-checking procedures is required, which allows for rapid iteration of design options based on sound and trustworthy data management and assessment schemes.

Surmounting these challenges requires a highly effective virtual-product environment capable of running digital MDA and MDO processes of very high complexity. These processes must be integrated with a common geometrical description of the aircraft that includes all relevant system details, commonly known as the master model. Concurrent development of the master model requires sharing design knowledge within the virtual-product engineering team at unprecedented levels; otherwise, unacceptable losses of quality and even failure of the project will be the result. The huge number of design parameters involved may lead to extremely high computational efforts and a lack of transparency on the optimization advancement. The desire for efficient computation calls for effective product data and life cycle management (PDM / PLM) and continuous model validation, which is a particular challenge for technologies with little experience or background knowledge.

Embedded in a virtual-product environment, effective MDA and MDO capabilities bear the potential to reduce the risk-intensive physical testing and demonstration phases to an absolute minimum. However, to leverage this potential, accuracy and reliability of MDA and MDO capabilities have to be raised to a level where they match actual physical testing. Thus, they must continuously be reconfirmed and validated through a deliberate combination of simulation and physical tests on each level of design, from the single component up to the full aircraft system, always considering the full product life cycle and the operational environment. Only when realizing this prerequisite will engineers and managers build up the confidence to trust such methods and base future strategic decisions on their results.

Synthesis

Multi-disciplinary optimization (MDO), based on a combination of low- to high-fidelity numerical simulation methods, is on the verge of bridging the existing gap between conceptual and preliminary aircraft design. This will enable the use of physics-based methods to cover complex multi-disciplinary interactions at an early stage in the overall aircraft design process, and will be of great importance for reliably designing enhanced conventional as well as innovative unconventional aircraft configurations. Thus, there is a clear need for research with regard to the use of multi-fidelity, multi-mission MDO for realistic aircraft configurations with many design parameters including all relevant constraints. Artificial intelligence (AI) and machine learning (ML) will help to incorporate existing design knowledge and data for improved design decisions. The ultimate goal is to perform a robust MDO, i.e. to optimize an aircraft configuration subject to flight physical and operational constraints in such a way that it is less sensitive to operational or geometrical uncertainties, parameter variations, disturbances and other interference.

To ensure that the virtual-product environment has industrial reliability, high-fidelity multi-disciplinary design tools are required, where high-fidelity means that the corresponding methods and tools are based on first principles, i.e. the underlying physics are represented by their fundamental laws. High-fidelity simulations require the use of computer-aided design (CAD) tools for geometry definition, and at least computational fluid dynamics (CFD) and computational structural dynamics (CSD) for flight physics analysis. Due to the high computational effort, such simulations have to run on high-performance supercomputing (HPC) systems.

Future MDO processes to establish a reliable digital foundation for designing sustainable future aircraft will have to feature at least the following capabilities in the simulation methods and tools involved:

- All methods and tools allow for coupling of the main disciplines relevant for flight physics assessment (e.g. aerodynamics, structures [stiffness and masses], systems [flight control for trim and redistribution of loads] and engine effects).

- Modelling representation may vary from “fast and approximate” to “costly and accurate” (e.g. structural representation by beam or FE model), but all model properties are distinctly configured and consistently checked (e.g. beam properties are continuously updated with the FE model).

- Local design changes through human interaction are admissible and feasible. The results being processed in a separate work space can be checked through preliminary integration into a multi-disciplinary master model to enable direct feedback of such local changes on overall performance. Human interaction is supported by making engineering knowledge of all relevant design disciplines accessible.

- MDO processes are continuously monitored by suitable AI algorithms to identify primary design parameters or combinations thereof, to improve computational efficiency, and to make the process transparent to the design team. Employing sensitivity analysis, other algorithms monitor the quality, such as by checking for numerical errors, model uncertainties, parameter sensitivities, imbalance of computational resources and convergence, and adapt the solution process accordingly.

- All data generated during the various design processes are organized on appropriate PDM platforms, where data configuration and management methods make these data available for current and future designs to continuously enlarge and update the knowledge base (inherent knowledge capturing). This might be organized and exploited by specific knowledge management tools, optionally employing machine learning or other AI methods.

To leverage the full potential of MDO, substantial research efforts have to be directed towards developing suitable software for product virtualization, multi-disciplinary analysis and optimization, as well as advanced reduced order models with consistent integration into the master model to speed up the design process by sufficiently reflecting relevant functional dependencies. Alongside these digital technologies, the correct, reliable and efficient physical representation of all technologies and their combination is of paramount importance. Thus, rigorous efforts in advanced physical modelling for aerodynamics, structures and flight dynamics are mandatory. To achieve the necessary accuracy and to establish clearly defined quality margins, consequent and consistent verification and validation efforts have to be pursued on carefully validated and verified test benches, as well as by wind tunnel and flight test campaigns. The accompanying generation of scientific and engineering knowledge will require development and application of methods for big data analysis combined with artificial intelligence (AI). Finally, to leverage the full benefit of numerical simulation with high-fidelity tools for future design and development, it is an absolute prerequisite to establish a fully digitalized engineering environment with seamless PDM access to all geometrical, technical and operational data. This will enable the consistent conversion of data into information, then into meaning or patterns, i.e. knowledge, and subsequently into design decisions.

3.4 Certification Aspects

Introduction

The existing CS 25 / FAR 25 certification regulations provide a solid basis for the development and safe operation of large civil aircraft. These regulations are based on many years of experience in classic aircraft construction.

As mentioned in *Chapter 2.2.2*, manufacturers' internal requirements and certification regulations for aircraft design have grown over the decades. In order to take a major step towards energy efficiency in aviation, the certification regulations must also be carefully analysed and adapted in individual cases.

The introduction and gradual expansion of the **Extended-Range Twin Operations Performance Standards (ETOPS)** for aircraft turbine engines can be seen as an example of a successful certification requirements challenge. Here, a strategy was developed that – based on successively demonstrated reliability in operation – led to routes being flown today with two engines that were previously reserved for four-engine aircraft, with correspondingly much lower fuel consumption.

Potential

Taking the gradual evolution of ETOPS regulations as a guideline, other requirements and regulations may also be deliberately and successively challenged, such as, e.g. the use of numerical simulation methods and the application of composite materials. Improved analysis and simulation methods for structural load-bearing behaviour offer large potential for weight reductions. The certification requirements (ref. CS 25.571) often mention "supported by test evidence". In principle, today's simulation methods allow the combination of load cases and failure scenarios that tests cannot even map. In this respect, simulation-based certification can now make more accurate statements than tests, and the conservatism of testing the building block is no longer necessary.

As discussed in *Chapter 2.2*, "no growth" of "uncritical" (>LL capability) impact damages is a key asset and contributes to the superior in-service behaviour of carbon fibre composites. As per current regulations, restoration of UL capability is mandatory. Thus today, the no-growth advantage only provides an advantage for the grace period between detection and repair: the repair effort can be moved to a planned maintenance event. Until then, the damaged area can be covered by cosmetic repair.

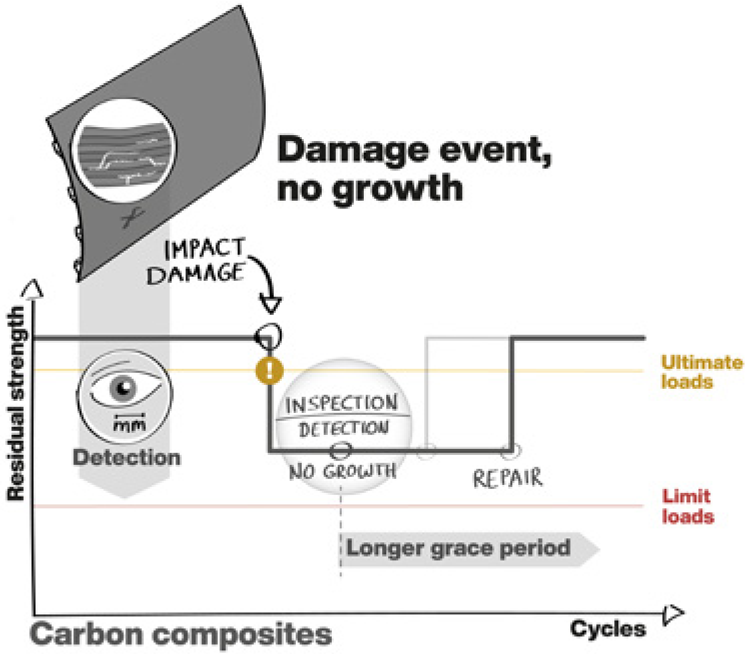

Figure 20: The no-growth property of CFRP structures allows the UL criterion to be questioned

A modified concept may utilize this advantage much more, subject to the successful development of a new certification approach. The factor of safety can be reduced, the *50%* margin can be challenged because of no-growth, and a margin to ensure timely detection is not necessary. Another concept could be to remove the need to restore UL capability; a cosmetic repair is sufficient to ensure safe operation until the end of the aircraft's life.

There is also large potential in the load assumptions, where, e.g., the vertical *2.5 g* manoeuvre may be challenged. Modern flight control systems will prevent this load case to a sufficiently high probability, which will have a significant impact on the wing sizing.

The same applies to "hard landings", whose high accelerations often dimension in the fuselage area of the airframe. Automatic landing combined with reliable wind-shear detection systems may offer the potential to reduce the *10 ft/s* requirement. The same applies to tail strike protection.

Gust loads and clean air turbulence pose an increased risk to safe operations, especially with climate change and global warming. This may lead to a change in the load envelope.

Here, mitigation may be achieved by the development of advanced flight control systems combined with advanced detection systems like LIDAR (cf. *Chapter 2.3*).

The fuel reserves prescribed today could also be challenged with the development of modern flight management systems and ever-improving weather forecasts.

This list is not exhaustive. However, certification requirements need to be challenged for an improved energy balance for future aircraft based on new materials, construction methods, simulation methods and diagnostic and predictive technologies.

Challenges

Safety is non-negotiable. All new methods and technologies to be introduced must result in at least the same if not a higher level of safety for the aircraft than the current – already very high – status quo. Accordingly, a careful and critical approach must be taken to the further development of certification regulations.

Suitable scenarios for the step-by-step development of regulations between OEMs, operators and certification authorities must be defined, which guarantee maximum safety through new experiences in each individual test step – comparable to the amendment of ETOPS requirements based on technology development over recent decades.

However, if one considers, e.g., the challenges that LH_2 as an energy source and the associated technologies pose for future aircraft system approvals, the urgent need to develop such stepwise adaptations and/or changes to regulations becomes mandatory.

Synthesis

As outlined at the beginning of this document, the drastic reductions in energy consumption require a paradigm shift from the current, well-established “incremental improvement” to a “step change approach”, under the mandatory condition of maintaining or even improving the current level of safety. A way to master these contradictory requirements may be envisaged by breaking down the step change approach to drastically new technologies into discrete levels, where only successfully meeting the challenges of a given level makes it possible to proceed to the next:

- For the first level, the **physical potential** has to be rigorously identified, i.e. does compliance with all physical laws really provide the expected improvements?

- Second, **technical feasibility** has to be established, i.e. is it possible to achieve the necessary material properties (with adequate manufacturing processes), system functions, sensor capabilities, power and energy densities, etc.? Attaining the second level will show how much of the theoretical potential will remain, making it possible to decide whether further investments will be justified.

- Then the third level – most critical for civil aviation – needs to be reached, namely **integrating the new technologies** into a (theoretical) new aircraft design and proving that the integrated new technologies will fulfil system reliability requirements and will eventually meet certification criteria. In this integration the effects on future operations, including maintenance, have to be properly assessed.

- The fourth and last level comprises **aircraft system validation** by simulation-based analysis, specific ground tests and early application on flying testbeds to finally verify the expected improvements and to ensure practical aircraft feasibility.

Especially for the first three levels, the sequential path from one to the next has be deliberately followed: If reliability concerns are raised too early, at levels one and two, promising technologies may be dropped without investing in a longer but eventually successful development phase. However, the advancement to the third level only after having effectively completed levels one and two must never be compromised, since in civil aviation safety is not negotiable. In this context, for future certification processes the current certification rules should be critically reviewed to enable the introduction of new technologies and operations through new and/or alternative means of compliance. It should, however, be clear that flight safety and the corresponding certification processes must never be compromised solely by demanding the implementation of "disruptive changes".

4. The Air Transport System Level

In the previous chapters, the energy efficiency of an individual transport aircraft was addressed, and technological pathways for airframe technologies as well as for new aircraft configurations were outlined to achieve a reduction of energy consumption by *50%*. With respect to the complete air transport system (ATS), it is, however, obvious that the sum of all individual aircraft is only one component of this system. Thus, aircraft design cannot be regarded in isolation, but all dimensions of the current economic, ecological and technical boundary conditions have to be considered. The dimensions spanned, e.g. by effects of aircraft fleet operation, by effects of technologies on aircraft configuration and by the time when certain technological means become available, will have significant impacts on the final design of a particular aircraft for a particular mission under particular market conditions. To achieve an ecologically and economically viable and competitive air transport system, i.e. globally sustainable air transport, all other components such as air traffic management, air and ground operations, airport infrastructure, maintenance, repair and overhaul, aircraft recycling in manufacture and disposal, etc., have to be taken into account. Here, not only energy efficiency but climate compatibility as a whole has to be addressed, meaning the complete ecological footprint of aviation has to be reduced. It is well beyond the scope of this document to address all of these topics, and thus the focus was set on energy-efficient aircraft technologies. However, to at least look somewhat beyond these individual aircraft technologies, in the following three sections, the performance of the **air transport system**, **air traffic management** and **life cycle considerations** will be briefly touched upon.

4.1 Air Transport Performance: The Significance of Flight Speed

Introduction

Flight speed is one of the most decisive factors for aircraft performance. For economic reasons, today's long-range aircraft fly at high speeds that are close to or even slightly exceed the speed resulting from maximizing the product of flight speed *V* and aerodynamic efficiency *L/D* (lift / drag), *V*L/D*. However, not just economic factors favour high flight speeds: if demand for air transport continues to increase by doubling every *15 years*, it is of paramount importance that the performance of air transport, i.e. achieving a high amount of revenue passenger kilometres in a given timeframe, can cope with this demand (revenue passenger kilometres, RPK: number of revenue-generating passengers times transport distance). For ecological reasons, this means that the total amount of energy required has to be minimized while maximizing the timely transport capacity for an ever-increasing number of passengers. Consequently, if one wants to make air travel available for an increasing number of global citizens, it may be economically as well as ecologically sensible to optimize aircraft design for high flight speeds at the maximum *V*L/D*, even if the minimum energy consumption of a particular aircraft will be achieved when designing it for the highest aerodynamic efficiency at the maximum *L/D*, as addressed in *Chapter 2.1* on drag reduction.

Potential

From the Breguet range equation, it follows that to maximize range, the product *V*L/D* has to be maximized. The theoretical assumption here is that the **thrust-specific fuel consumption (TSFC)** of the propulsion system is proportional to the required thrust but independent of the flight speed. This strictly holds only for jet engines with very low bypass ratios (BPR). In the case of propeller-driven aircraft, the **power-specific fuel consumption (PSFC)** is theoretically assumed to be independent of flight speed (up to a certain maximum). The corresponding TSFC then increases linearly with flight speed, and for such aircraft, *L/D* has to be maximized to achieve maximum range. At comparable weight and aerodynamic efficiency, the optimal speed for maximum range for a propeller-driven aircraft is about *25%* lower than the optimal speed for a corresponding jet-powered aircraft. Flying the propeller-driven aircraft at the speed corresponding to maximum *V*L/D*, its energy consumption will increase by about *15%* compared to flying at maximum *L/D* (cf. *B. H. Carson, 1980*). From the square / cube scaling law, it can be deduced that wing loading (weight per wing area) is proportional to the square of the flight speed, meaning heavier aircraft have to fly faster. To minimize the energy consumption of a particular aircraft, the main design drivers are therefore the aircraft's weight, its aerodynamic efficiency and the fuel consumption characteristics of the propulsion system. Depending on the speed required by the weight of the particular aircraft, the best-suited propulsion system may then either be propeller-based propulsion, an open rotor architecture, or an ultra-high bypass ratio (UHBR) turbofan propulsion system (cf. *Chapter 2.4*).

Due to the substantial BPR increase in modern energy-efficient propulsion systems like open rotors and/or UHBR turbofans, the corresponding fuel consumption characteristics tend more and more towards those of propeller-based systems. Thus, for aircraft with very high BPRs, the highest possible reduction of energy consumption will be achieved with designs for flight speeds close to the maximum *L/D*. Flying at this energy-efficient speed, the minimum amount of energy is required for a certain amount of RPK. Since this speed is about *25%* lower compared to the flight speed at maximum *V*L/D*, travel time will increase by about *33%* (not including the take-off and landing phases). Passengers and airlines will have to adapt to this substantial change.

Flying the fleet's aircraft at the minimum energy speed degrades transport performance by a factor of *0.75*, compared to flying all aircraft at the speed of maximum *V*L/D* (since speed is reduced by *25%*). To still obtain the same transport performance, i.e. the same RPK should be achieved in the same timeframe, theoretically the number of aircraft has to be increased by a factor of *1.33* (the reciprocal value of *0.75*). This significantly increases the cost of ownership, maintenance and crew. This is the main reason why at present the fierce competition among airlines precludes significant reductions in flight speed.

Challenges

While the above analysis of design drivers that determine the cruise speed of current commercial aircraft has guided the design of present aircraft, future aircraft manufacturers and aircraft operators will have to cope with new external boundary conditions that affect all aspects of the aviation system:

- The worldwide demand for air transport depends on the **global economic development**. This demand affects the operational constraints on the needed performance of the air traffic system, which itself depends on the speed of travel. The future development of economies is, however, rather uncertain today.

- **Availability and cost** of hydrogen-based as well as carbon-based fuels (SAF) will likely impose rather hard constraints on aircraft design. If, e.g., the cost of SAF amounts to five times the price of today's kerosene, that would clearly change the economic trade involving the cruise speed as elaborated above and lead to lower cruise speeds. It is, however, uncertain when the cost of low-CO_2-emission fuels will become a severe constraint in the manufacture and operation of commercial aircraft.

- National and international **regulation on climate change** could become another external constraint within the foreseeable future. At this point in time it is known that the forcing of climate change depends on the atmospheric conditions at the location of flight trajectories. It appears that at least significant parts of current flight trajectories are located at altitudes with rather strong atmospheric forcing. Again, however, it is uncertain if and when international regulators of aviation will introduce additional constraints on the operation of commercial aircraft to minimize climate change.

- The **availability of technologies** to radically affect fuel consumption may be viewed as a key for opening new design spaces to adapt aircraft performance to the needs of drastically changing markets and external boundary conditions. However, it is well known that most technologies, e.g. for reducing aircraft fuel consumption, introduce additional cost of ownership and often create additional maintenance cost. As explained in more detail in *Chapter 2*, technology development also comes with the uncertainty that some objectives can only be partially met. In addition, the time it takes to achieve a technology readiness sufficiently high for market introduction is often uncertain as well.

These externally imposed boundary conditions can be understood as new, highly challenging dimensions of the problem of designing, manufacturing and operating commercial aircraft in an air transport system of the future.

Synthesis

The new external boundary conditions introduced above contain rather uncertain parameters. To gain some insight into their possible consequences, two specific "extreme" scenarios may be defined, where a future reality may lie somewhere in between:

The first scenario describes an air transport system with moderate mobility demands, resulting in rather limited annual growth rates over time, and hence the available infrastructure in terms of airspace and airports will not be challenged. However, a lack of available SAF and/or hydrogen leads to extremely high fuel costs (e.g. a factor of five compared to kerosene). In addition, international regulation calls for reduced flight altitudes for most of the flight trajectories. In this case, reduction of energy consumption will become the ultimate priority for air transport of payload over a distance (i.e. minimizing energy per RPK). Then, with future propulsion systems featuring higher and higher bypass ratios, the corresponding optimal aircraft design speeds will be close to the maximum of the aircraft's aerodynamic efficiency *L/D*, and competitive aircraft must take advantage of all viable technologies for reducing fuel consumption.

Second, a scenario is considered that is characterized by significantly larger annual growth rates that bring the available infrastructure of the air transport system close to its limit. It is further assumed that "green" fuels (SAF and H_2) are available at a moderate cost increase (e.g. a factor of two compared to kerosene). In this case, the energy required for the close-to-optimum transport performance is to be minimized, i.e. achieving the minimum amount of energy for transporting a payload over a distance in the shortest possible time. Hence, the flight speed should be increased corresponding to the maximum *V*L/D*, as outlined above. The higher transport performance also leads to a higher utilization of the aircraft, which is beneficial from an economic point of view. Since in this scenario as well the cost of alternative fuels is substantially higher than for kerosene today, there will still be the pressing need to employ advanced technologies to reduce fuel consumption for the sake of aircraft competitiveness.

It is important to note that all scenarios that appear acceptable from a long-term global socio-economic viewpoint (the two extremes outlined above and any in between) will require the development of advanced technologies that achieve drastic reductions in fuel consumption. Moreover, the availability of such technologies appears to be the only option to overcome the four external boundary conditions listed above that can be directly influenced by the European stakeholders of commercial aviation.

The requirements from these different scenarios will have consequences for the importance of different technologies in aircraft design. Flying at maximum *L/D* requires a *1:1 ratio* of induced and viscous drag. Flying at maximum *V*L/D* requires ratios between *1:2* and *1:3*, depending on cruise climb and thrust setting. Therefore, when flying at higher speeds for high transport performance, it becomes more important to reduce viscous drag. Without substantially reducing viscous drag, the reduction of induced drag by increasing span (or aspect ratio) will not result in further benefits (see remark at the end of *Chapter 2.1*).

The optimal speed is also related to weight (heavier aircraft have to fly faster). Thus, energy-efficient aircraft with different weights will have to fly at different speeds (and altitudes), and future air traffic management (ATM) systems will need the capability to manage the resulting diverse air traffic situations.

4.2 Air Traffic Management and Operations

The core task of today's air traffic management (ATM) is the conflict-free management of flight movements through the airspace to allow airlines safe operation of their aircraft fleets. Today, environmental aspects are already taken into account, such as avoiding holding patterns, but are left to manufacturers and operators. In the future, however, air traffic management and fleet operations by airlines may become as important as the individual vehicles, where air traffic management will not only provide conflict-free air traffic but also become a decisive factor for efficient fleet operations in an ecologically sustainable transport system.

In the context of air transport performance, it has already been addressed that for an economically and ecologically viable and competitive air transport system, individual 4D flight-path optimization for each aircraft from departure to arrival becomes an indispensable prerequisite.

Concerning other contributions by ATM and operations to sustainability, four other individual topics (formation flight, environmentally optimized flight paths, more direct flight connections, aircraft noise) will be addressed below; sustainable air traffic management and operations can, however, also have other forms.

- **Formation flight:** When creating lift, a flying aircraft generates a pair of counter-rotating vortices in its wake. Far enough behind the aircraft generating these vortices, the updraft velocity field can be used to provide part of the lift for an aircraft flying behind it, which leads to a reduction in the angle of incidence and thus also in drag. For transport aircraft, a reduction of up to *50%* of the induced drag and on average a reduction in the overall drag of *~10%* is forecast at a Technology Readiness Level *TRL 3* (consider the ratio of induced to viscous drag at cruise is around *1:2*). In a first Airbus demonstration campaign in 2021 with two A350 aircraft on a transatlantic long-range mission, a fuel burn improvement of over *5%* could be demonstrated. It should be noted, however, that this type of flying will probably increase the unsteady loads on the wing and vibration of the aircraft in flight. Besides being a potential passenger comfort issue, this can affect the service life of the aircraft and may require a reinforced wing or load reduction systems; see also the concluding remarks below.

- **Environmentally optimized flight routes:** The receptivity of the atmosphere to emissions varies at altitude and latitude, depending on many factors such as humidity, dew point, air pressure, composition / partial pressures, etc., particularly with regard to the formation of contrails and cirrus clouds (induced by soot, unburned CH substances or contrails). Clouds have both a warming effect, as they prevent heat from being radiated from ground to space (greenhouse effect), and a cooling effect, as they reduce incoming solar radiation; science currently assumes that they have a warming effect overall. With knowledge of the respective effects, future air traffic management could specify the ideal trajectory at which the effect of a flight's emissions is the lowest. For long-haul flights, this would mean that the route must be adaptable even during the flight, as the properties of the atmosphere can certainly change during a 14-hour flight. If there is a global agreement on atmospheric models, this would lead to dynamic route planning, again strengthening the need for 4D flight-path optimization as stated above. From today's perspective this would have the greatest impact of all on the ecological footprint, since this measure can be applied to all flights without designing, manufacturing and introducing new aircraft. However, this will lead to more flying in the troposphere in terms of the selected flight altitude, and wing loads will increase, which will reduce service life. As a consequence, designs of future aircraft will have to be more robust to deviations from the nominal design point; they will exhibit increased wing weight due to reinforcements or, to avoid any weight increase, the development and application of advanced load-reduction technologies will be required (*cf. Chapter 2.3*).

- **More direct flight connections:** New network structures can lead to higher shares of direct flights (i.e. reduction of stop-over trips). Current networks and connections are largely influenced by the evolution of airlines (mainly originating from national carriers) being restricted in their operations by bilateral governmental agreements based on ICAO's Freedoms of the Air. These legal factors pose significant limitations to the business models for airlines when it comes to flexibility in network structures and routing of passengers (e.g. hub-and-spoke systems being a consequence). Relaxations could provide the basis for more efficient routing options for the individual passenger trip, leading to substantial savings in the ecological footprint of the individual trip (especially with long-range travelling).

- **External aircraft noise:** The goal of increasing efficiency is primarily formulated with respect to reducing fuel consumption, but it should also be understood with a more general view towards sustainability that includes social aspects. Aircraft noise has been one of the most important issues in aviation, not least for reasons of social acceptance, but also because it defines the throughput of passengers at airports (certification rules for aircraft, flight restrictions and night curfews). This document does not address aircraft noise, but the topic will at least be touched upon here.
  - The social aspects of noise include not only the burden on residents around airports (external noise) but also on passengers (cabin noise). The latter also has to do with the effects of, for example, aerodynamic measures to increase efficiency. Nevertheless, cabin noise will not be a topic here. This leaves the source noise to be addressed in the context of air traffic management. The main sources of external noise in slow flight are the high-lift system, landing gear and engine. For a given source noise, the flight path is the only way to influence

the noise effect on the ground. The choice of a suitable flight path depends crucially on the flight performance, i.e. the efficiency-enhancing measures described in the previous chapters also affect the ability to climb or descend steeper or faster. However, this gives rise to another challenge: different aircraft with different flight performances can only follow a given flight path with low noise to a limited extent. For example, a continuous descent approach (CDA), or slow flight in general, is difficult with a mix of different aircraft when approaching an airport, as the glide ratios will differ but a defined separation must be maintained for safety reasons. As with environmentally optimized flight routes, this ultimately leads to a 4D flight-path optimization for each individual aircraft, during cruise flight due to the environmental impact and during approach and departure due to the noise.

4.3 Overarching Aspects of Life Cycle

Almost the whole footprint of an aircraft is related to its operation in the air transport system; production's share of the overall impact, including development and certification, is small. Thus, it is important to maintain any increase in efficiency over the entire service life, not just when it is delivered to the first customer. The necessary expenditure, e.g. with regard to additional **Maintenance, Repair and Overhaul (MRO)** activities, must therefore be included in efforts for increasing efficiency right from the start.

This results in three overarching topics beyond the pure development and delivery of new, more efficient aircraft:

- In general, an aircraft is kept in service by the first customer for *7–10 years* and then sold to another airline; in the leasing sector, too, these airline changes occur over the course of the aircraft's lifespan. To maintain ecological efficiency in the sense of the ecological footprint, it must be ensured that the necessary MRO measures are followed by all owners until the end of life.

- One frequently cited way to reduce the ecological footprint is to replace older aircraft with new, more efficient aircraft as quickly as possible. Since the recycling rate for aircraft is less than *100%* today and will probably remain so in the long term, early decommissioning creates additional environmental pollution, e.g. in landfills, and this must therefore be included in the overall balance.

- To assess the benefit of an efficiency increase at the ATS level, it is important to weight the effect of various measures at the global fleet level: for example, a measure to increase efficiency by *2%* on *15000* existing aircraft (e.g. through a wing modification) can exceed an efficiency increase of *10%* on *1000* specific new aircraft in terms of overall effect. Thus, efficiency-increasing "retrofit solutions" should also be rigorously developed and brought to market. Note that the technological basis for such retrofit packages is well aligned with the technologies outlined in this document.

MRO has similar issues to pure aircraft production in terms of parts, supply chains, production, assembly, etc., but these issues are present in MRO over the entire lifespan of the aircraft. It is suggested that, like the *50%* increase in efficiency of a new aircraft described in this document, a *50%* increase in efficiency in MRO should also be developed. This means that the circular economy, or in this case circular aviation, must be considered as a core element of sustainability: the ecological footprint is not only shaped at the beginning of the production process and at decommissioning, but throughout the entire life cycle, across all operators and across all parts, especially with a view to the continued use of parts, even if their flight approval is lost.

4.4 Further ATS Aspects

First of all, for the sake of completeness, it should be noted that some overarching points were not considered in this section, e.g.:

- **Onboard personnel:** Onboard personnel account for a substantial share of direct operating costs DOC. With regard to the ATS, a reduction, e.g. through increasing automation of flight operations to the point of autonomy and automated evacuation systems, also offers potential for increasing efficiency.

- **Ground processes:** Like flight operations, ground processes such as de-icing, boarding/de-boarding, refuelling and taxiing also have an impact on the ecological footprint. There is potential for optimization and efficiency improvements here, so an overall assessment should also take these aspects into account.

- **Aviation as part of the mobility system:** When considering mobility from door to door (D2D), enhanced transportation-network aspects also need to be considered. A more stringent integration of the air transport system with the ground transport system, especially on shorter routes, may lead to a more efficient mobility system. Shifting of some very short-range flights to the ground may also show positive effects on the capacities of already congested airports. From a more radical perspective, the transport system as a whole may also be considered as an integrated logistic system, where a transport integrator may choose, based on the D2D ticket acquired by the customer, the best assets to achieve the highest transport efficiency.

In any case, in addition to direct modifications of the vehicle through efficiency-enhancing measures, its operation in the air transport system also offers great opportunities for increasing efficiency. The overarching aspects of increasing efficiency with regard to the ATS air transport system can therefore be summarized as follows:

Flying is not an isolated mode of transport but part of a seamless, intermodal transport system “from door to door” for both freight and passengers. Thus, in the future the operation of aircraft should be part of an overall system of mobility, energy and safety. The aim must therefore be to optimize these three overarching systems holistically, with each system making its own contribution, where aviation, among other measures, will contribute through the development and use of the technologies described in this document.

5. Summary and Outlook

This document sets out the possibilities for drastically reducing the fuel consumption of future commercial transport aircraft, based on the following premises:

- The technologies described address the airframe of commercial transport aircraft. The efficiency increase potential per technology ultimately depends on the specific aircraft class (regional, medium- or long-haul / propeller or jet / high subsonic or transonic / classic or new configuration), i.e. concrete values for improvements require a specific analysis of the different technologies on a case-by-case basis, both individually and in their interaction.

- Final overall improvement gains can only be estimated on the basis of a specific aircraft configuration.

- The technology maturities of the individual technologies described here are mainly still below *TRL 6*, i.e. some of the technologies may not reach product maturity before 2040 or even 2050.

- The envisaged implementation of a technology into a product is based on the possibilities available today (materials, IT methods, verification procedures, etc.). However, further possibilities may emerge in the near future that will allow faster and/or alternative ways to mature the technology.

- The technologies described are not weighed up in a kind of competition, even against other measures, e.g. in operations; instead, all available technologies are used in an idealistic way to maximize efficiency gains. The premise of this document is to define the technological envelope for achieving ultimate energy efficiency, not to outline the next product from any manufacturer.

- In the technology descriptions in this document, the increase in efficiency has the highest priority. For a specific aircraft program, other criteria such as current maturity, costs, development time, etc. will have to be taken into account. Therefore, it should always be clear that it is ultimately up to the Original Aircraft Manufacturer (OEM) to decide which of the technological options outlined in this document will be feasible under prevailing market conditions when launching a new product.

The most important conclusion is that if sustainable aviation is to become a reality, the technology maturation required for implementation must begin today. The classic duration of approx. *1.5–3 years* per TRL level means that the technologies described, some of which are currently at a TRL level of approx. *3*, will take around *15–20 years* to mature to a *TRL 9* for product maturity – consequently, only if a start is made today will these technologies be available before 2050. Interim results may be achieved earlier, and individual technologies may be matured more quickly. The core message of this document is that a *50%* fuel aircraft, i.e. an aircraft with *50%* less fuel consumption, is possible by using the technologies described here, and with respect to the challenges of commercial aviation it is therefore absolutely desirable and worthwhile to develop them towards product applicability.

Accordingly, the authors urgently recommend pursuing these technology paths instead of focusing solely on alternative fuels with the aim of climate neutrality.

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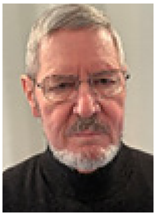

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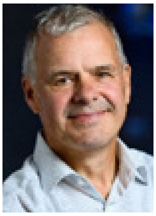

Figure Index

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