Decarbonising Aviation: *innovation and digital at the heart of strategies*

sopra steria next

Contents

Introduction

Charting a New Course for Aviation

The dawn of aviation in 1903 marked the culmination of centuries of human ingenuity and perseverance. Just six years later, the first international air show in December 1909 showcased the rapid progress of the fledgling industry, with luminaries like Blériot, Delagrange, Breguet, the Wright brothers, Clément Ader, and Santos-Dumont presenting their revolutionary flying machines. The advent of modern commercial aviation, propelled by turbojet engines, ushered in an era of unprecedented global connectivity, fostering cultural exchange, and driving economic growth on both local and global scales.

Throughout its history, the aviation industry has been characterized by relentless innovation and a pioneering spirit. The imperative to transport more passengers faster, farther, and more economically has fueled a continuous quest for enhanced energy efficiency. **Since the first oil crisis, this quest has yielded impressive results, with fuel consumption decreasing by approximately 1% annually. Each new generation of aircraft boasts a remarkable 25% improvement in efficiency over its predecessor.** Occasionally, technological breakthroughs have catalysed extraordinary leaps forward, as exemplified by the A321neo. This aircraft incorporates cutting-edge materials like titanium aluminide and 3D composites, along with advanced manufacturing processes such as additive manufacturing for fuel injectors.

These advancements have largely been driven by fierce competition among airlines and manufacturers. The rise of low-cost travel over the past three decades has revolutionized the industry, prioritizing cost optimization and operational efficiency. This model has spurred tremendous growth in air transport, particularly in medium-haul routes catering to leisure and tourism. While ticket price[1] remains the primary consideration for most passengers, **environmental concerns have rapidly ascended to become a strategic imperative for the industry.**

The environmental impact of aviation has become increasingly apparent, both in scientific fact and public discourse. Between 1940 and 2018, the aviation sector's contribution to total anthropogenic CO_2 emissions surged from 0.7% to 3.8%[2].

This trend is poised to accelerate dramatically if left unchecked, given the projected growth in air travel. The International Air Transport Association (IATA) forecasts passenger numbers to reach 6.7 billion by 2032, 7.3 billion by 2034, and potentially 16 billion by 2050. This explosive growth is fuelled by a trifecta of factors: demographic expansion, economic development, and rising living standards, particularly in emerging economies.

As the aviation industry stands at this critical juncture, it faces the dual challenge of meeting strong demand while drastically reducing its environmental footprint. This imperative for sustainable growth will require unprecedented collaboration, innovation, and investment across the entire aviation ecosystem.

1 - French National Assembly (January 12, 2022), Information report [...] on the future of the French aeronautics industry (no. 4892).

2 - Excluding land-use change, as established by David S Lee et alii, "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", Atmospheric Environment, vol 244, 1/01/2021. The environmental impact of the aviation sector is multifaceted. Three factors of climate disturbance can be identified: emissions of CO_2 and other GHGs, contrails and induced cloudiness, as well as emissions of nitrogen oxides. While scientific uncertainties vary in estimating the relative share of these different contributions, it is certain that the total impact is significant.

A Resolute Industry Commitment to Sustainability

The aviation industry has awakened to its ecological responsibilities, demonstrating a robust commitment to change. This shift is exemplified by the landmark **Toulouse Declaration** of May 2022, where 42 nations united in calling for the complete decarbonization of air transport by 2050, aiming for net-zero emissions. The International Air Transport Association (IATA) has embraced this ambitious goal, projecting that the industry could eliminate a staggering 1.8 gigatons of carbon emissions by 2050[3]. This commitment is further reinforced by the Long-Term Global Aspirational Goal (LTAG), a framework established by the industry in 2021 and subsequently endorsed by the International Civil Aviation Organisation (ICAO) at its 41st Assembly in October 2022. The LTAG represents a comprehensive, globally coordinated approach to sustainable aviation.

A key mechanism in this sustainability drive is **CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation)**, implemented by ICAO in 2016 and operational since 2021. This innovative program commits the sector to carbon-neutral growth, initially on a voluntary basis. It will become mandatory for all airlines by 2027. CORSIA's objective is to offset annual CO_2 emissions exceeding a baseline level (set at 85% of 2019 emissions) through the purchase of carbon credits. The scheme's reach is impressive, currently encompassing over 80 countries and accounting for approximately 80% of international air traffic. In parallel, the European Union has maintained its own emissions control mechanism, the EU Emissions Trading System (EU-ETS), for intra-European flights. This cap-and-trade system, originally designed for stationary carbon-emitting installations, has sparked debate within the industry. Both IATA and ICAO have voiced concerns, arguing that the EU-ETS may create confusion, potentially mislead stakeholders, and could have unintended consequences for both European and non-European airlines.

The coexistence of these different approaches – global (CORSIA) and regional (EU-ETS) – underscores the complex, multi-faceted nature of aviation's sustainability challenge. It highlights the need for harmonized, globally coordinated efforts to effectively address the industry's environmental impact while maintaining fair competition and operational efficiency.

As the aviation sector navigates this transformative period, it must balance ambitious environmental goals with practical implementation challenges. The industry's proactive stance, as evidenced by these wide-ranging initiatives, demonstrates its commitment to playing a pivotal role in combating climate change while continuing to connect the world.

3 - IATA, Press release no. 66: Net-Zero Carbon Emissions by 2050. https://www.iata.org/contentassets/dcd25da635cd4c3697b5d0d8ae32e159/2021-10-04-03-fr.pdf

Regulatory frameworks significantly shape production processes and operational practices in the aviation industry. Recent policy shifts[4] are actively promoting the mitigation of greenhouse gas (GHG) emissions through two key strategies: the adoption of alternative fuels and the implementation of more stringent energy efficiency standards[5]. **The environmental impact of an aircraft is overwhelmingly concentrated in its operational phase, accounting for approximately 90% of its total lifecycle emissions, according to Airbus' 2022 universal registration document.** This disproportionate effect stems from aviation's continued reliance on fossil fuels. Currently, these remain the sole energy source with sufficient density to power aircraft weighing hundreds of metric tons.

The 2023 Paris Air Show prominently featured decarbonization as its central theme. In response, French President Macron unveiled a significant public investment plan: 300 million euros annually from 2024 to 2030. This funding aims to develop an "ultra-clean aircraft" and its corresponding engines, designed to operate on both hydrogen and 100% biofuels. **However, the scope of investment required for industry-wide transformation far exceeds this figure. It necessitates substantial contributions from all sectors of the aviation ecosystem:** Aircraft manufacturers, Supply chain vendors, Airlines, Air traffic control organizations, Research institutions, Fuel suppliers, Government bodies. The scale and complexity of this transition underscore a critical need: extensive collaboration and information sharing among these diverse stakeholders. Only through such coordinated efforts can the aviation industry hope to achieve its ambitious decarbonization goals.

The environmental crisis is creating a complex, self-reinforcing cycle of challenges for the aviation sector:

1. Resource Scarcity: The increasing scarcity of natural resources is impacting every stage of an aircraft's lifecycle[6], from manufacturing to disposal.
2. Rising Costs: Energy and raw material prices are escalating, with fuel alone typically accounting for about one-third of a flight's total cost[7].
3. Financial Pressure: These rising costs are squeezing profit margins across the industry, potentially threatening the viability of some players.
4. Demand Risks: To maintain profitability, airlines may need to significantly increase ticket prices. However, this could lead to reduced demand for air travel.

This interconnected web of environmental and economic factors creates a vicious cycle: environmental degradation leads to resource scarcity and higher costs, which in turn may result in higher prices and potentially reduced air travel. Paradoxically, reduced air travel could slow the industry's ability to invest in sustainable technologies, potentially exacerbating environmental impacts in the long term.

The aviation industry stands at a critical crossroad, facing both immense challenges and unprecedented opportunities for reinvention:

1. Post-COVID Recovery: Following the pandemic, airlines, manufacturers, and their suppliers have undergone financial restructuring, often with government support.
2. Increased Investment: These newly restructured entities are now channelling significant resources into innovation and development.
3. Uneven Evolution: Certain aspects of the aviation sector will require more radical changes than others. These areas include Engineering, Operations management, Air traffic management.
4. Innovation Imperative: To address these challenges effectively, the industry must embrace new working methodologies, and Cutting-edge technologies.

This period of transition presents both risks and opportunities. While the costs and challenges are substantial, they also offer a chance for the industry to reinvent itself, potentially emerging more resilient, efficient, and sustainable.

The success of this transformation will likely depend on the industry's ability to:

- Collaborate across traditional boundaries
- Adapt quickly to new technologies and methodologies
- Balance short-term financial pressures with long-term sustainability goals.

4 - In France, the National Air Transport Strategy and the National Low-Carbon Strategy have been put in place to set these objectives. The Climate and Resilience Act and the tax incentives attached to the use of alternative fuels in France, the provisions of the Fit for 55 package at European level and the CORSIA program at international level are just a few examples of these regulations.

5 - But also, in another register, the promotion of alternative modes of transport, notably the train for short journeys. Some envisage a limitation in the volume of journeys for ecological reasons. Such a proposal could represent a supply shock on a scale equal to that of the Covid crisis, which, it should be remembered, led to an 8% drop in the aviation industry's workforce -- four times more than in the rest of the economy (Insee Première, no. 1882, December 2021, "Survey of the aviation and space industry in France in 2020").

6 - Carl Labergere, "Mechanics and materials in support of the energy transition and transport of the future", InterUT Safe and Sustainable Systems Colloquium, Compiègne University of Technology (UTC), February 2023.

7 - European Affairs Committee, Information report on the future and decarbonisation of the European aeronautics sector.

Aviation: four priority levers *for carbon neutrality by 2050*

Lever 1: Sustainable fuels (SAF)

Between

65%* and 53%**

See explanations opposite

Lever 2: New propulsion technologies (electric, Hy)

Between

13%* and 34%**

Lever 3: Efficiency of operations and infrastructure

Between

3%* and 7%**

Lever 4: Carbon capture and sequestration

Between

11%* and 6%**

Compensation : 8 %

* Source : IATA.

** Source : Waypoint.

Focus lever 1: ***Alternative*** Fuels

Sustainable Aviation Fuels (SAF), or alternative fuels, are a major weapon in the fight to decarbonize aviation. Some SAFs are derived from renewable resources like vegetable oils and agricultural waste, and they can be used in today's aircraft without major modifications.

Other SAFs, such as e-fuels, are produced using renewable electricity. However, their efficiency needs improvement for widespread use in current turbojet engines.

All SAFs must meet sustainability criteria defined by the International Civil Aviation Organization (ICAO) since 2016. These criteria include a minimum reduction in greenhouse gas emissions and protection against deforestation. Even stricter criteria focusing on ecosystems, biodiversity, human health, and society will be added starting in 2024.

By 2050, the aviation sector should ideally have access to 450 billion litters of SAF, representing 65% of its fuel needs[8], according to the International Air Transport Association (IATA). Both Airbus and Boeing have pledged to develop aircrafts capable of flying on 100% SAF by 2030.

While SAF production doubled in 2022[9], it remains a nascent industry. New producers are emerging, and infrastructure for manufacturing and distribution is developing around airports[10]. However, significant challenges remain. SAF currently represents only 0.01% of the fuel used by aviation (2018), and its availability is likely to face competition from other industries[11]. The high cost of SAF currently presents a significant hurdle to widespread adoption.

Focus lever 2 : Electric and ***Hydrogen***

Offering zero-emission operation, electric and hydrogen propulsion systems, are being examined by manufacturers with considerable investments earmarked for their development. However, these technologies entail a fundamental rethinking of aircraft design, limiting their scope of application and speed of implementation. In the case of hydrogen, the storage capacity in the aircraft, the need for extremely low temperatures (-253°C) for its liquid form, and the safety constraints required for such a system make it difficult to envisage an aircraft flying beyond short distances with a limited number of passengers before 2035 at the earliest, although significant hurdles remain in terms of storage and safety. As for electric power, the mass of the batteries and their limited charge mean that this alternative is mainly considered for light aviation or hybrid solutions, some of which are already operational (electric taxiing, school aviation, etc.).

Despite these challenges, the aviation industry has clearly taken full account of the need for decarbonization, and there is no shortage of initiatives, either autonomous or supported by governments.

8 - 7.9 billion litres in 2025, 2% of fuel needs.

9 - SAF production in 2022: 300 million litres, or 240,000 metric tons. https://wwwiataorg/contentassets/53dc669abd194d14bbecf9aa8eb1b09a/2023-06-06-01-fr.pdf

10 - In 2022, the IATA recorded 130 SAF projects and 85 SAF producers in 30 countries.

11 - This has notably led to a company like Air France seeking to secure its upstream supplies by investing directly in production capacities. Cf. La Tribune, "Air France-KLM invests directly in a green fuels plant in the United States", November 10, 2023.

Engineering new challenges

Balancing performance with constraints is a constant challenge in the aerospace industry. The pursuit of faster, farther, and cheaper flights has driven major investments in efficiency. One key area of **focus is weight reduction,** which has led to optimized passenger and freight transport, measured in terms of CO_2 emissions per unit (tCO_2e/km pax for passengers and tCO_2e/metric ton of freight/km for cargo). Air France's Horizon 2030 plan exemplifies this focus: they estimate that reducing the weight of all their aircraft by just one kilogram would result in annual savings of 69 metric tons of CO_2.

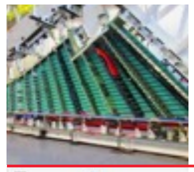
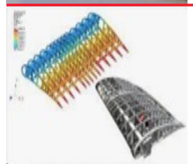
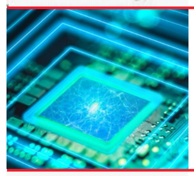
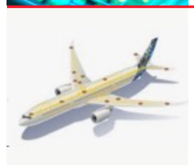
To achieve further advancements, industrial and academic research laboratories are actively developing innovative solutions. These innovations can be broadly categorized into five major families, encompassing both incremental and disruptive technologies[12]:

12 - Waypoint 2050 and Institut Montaigne, Archery Strategy consulting analyses.

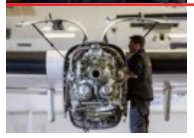
13 - CFRP (Carbon Fiber Reinforced Polymer).

14 - ELCOCOS (Enhanced Low-cost COmplex COmposite Structures): a European project to develop a composite door using liquid resin infusion (LRI) technologies.

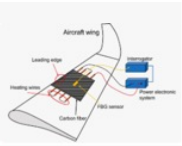
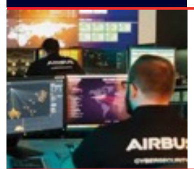
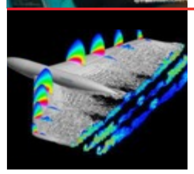
15 - Safran Seats and its project for a seat weighing around 9 kg, compared with an average of 13 to 15 kg for a seat today. Estimated savings: 0.5% to 1.5% of aircraft weight.

	New materials		Technological maturity (1 to 4)
	Smart composites	Improved material capable of increasing strength while reducing weight. E.g.: CFRP[13], ELCOCOS[14], titanium/composite seat[15].	3
	Smart structures	Improving aerodynamics and safety while reducing fuel consumption by adapting parameters such as wing shape, structural rigidity and vibration absorption: Smart Structure, Smart Morphing.	3
	Nanotechnologies	Integration of nanoparticles into materials, nanocomposite coatings, nanotechnology sensors and nanofluids for thermal management.	3
	Health Monitoring structures	Deployment of monitoring technologies (sensors) to assess the condition of aircraft/engines, as well as to collect, analyse and carry out preventive maintenance.	3
	Eco-friendly carbon fibres	Development of new, less energy-intensive carbon fibres (new polymers or biological waste instead of chemicals).	3

Industry 4.0

			Technological maturity (1 to 4)
	Factory 4.0	Intelligent, connected production environments integrating IOT, AI, advanced automation, data analysis, etc.	3
	Robotisation & intelligent automation	Use of robots in workshops for cutting, welding, component installation (e.g. exoskeletons), but also for automating quality testing of parts and structures, for maintenance and repair, and for flight testing.	4
	Additive Manufacturing	3D/4D printing using a manufacturing process that adds material layer by layer: FDM (fused material deposition), stereolithography (SLA), selective laser sintering (SLS), etc.	3
	AR-VR	Augmented reality to display real-time information in cockpits or assist maintenance technicians; virtual reality to recreate production or systems environments to simulate operations, processes, etc.	3
	Predictive maintenance	Anticipation of potential failures or breakdowns of aircraft components or equipment using data and advanced analysis.	3

New connectivity solutions

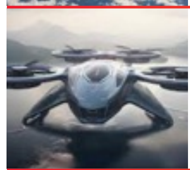
			Technological maturity (1 to 4)
	Smart sensors	Integration of sensors for real-time data collection, processing and transmission (navigation, atmosphere, obstacles, loads, constraints, fuel, engine, etc.): IOT, fly by wire, Sensor Platform system.	3
	Big data	Collecting, storing and utilising large quantities of data to facilitate decisions and extract meaningful information: Big Data, Distributed Computing, Distributed Solving of Global Optimisation Problems, Enhanced Situation Self-Awareness.	3
	Artificial intelligence	Architectures and algorithms (machine learning, deep learning) for designing autonomous systems, analysing data for predictive systems maintenance, optimising flight operations and performing flight simulations (aircraft learning).	2
	Cybersecurity	Protecting the computer systems, networks, data and information technologies used in the aeronautics industry against cyber threats: onboard systems, communication networks, air traffic systems, aircraft diagnostics/maintenance, etc.	3
	Advanced simulation	Using sophisticated computer models to realistically reproduce the behaviour of aircraft, systems and aeronautical environments: flight simulation, aerodynamic modelling, material/structural behaviour, engine performance, avionics systems, etc.	3

It will be necessary to ensure that any negative impacts of digital technology are offset by the positive gains associated with its use.

Green technologies

			Technological maturity (1 to 4)
	Electric motors and propulsion	Using electric motors to propel aircraft, using batteries or fuel cells.	2
	Renewable energies	Using new energies for aircraft propulsion: biofuels (SAF), solar energy, hydrogen, etc.	1 - 3
	Propfan	A turbojet engine in which the fan blades are located outside the engine nacelle (reduced drag, lower fuel consumption; disadvantage: increased noise and vibration).	2
	Eco-design	Integration of environmental considerations throughout the lifecycle of an aeronautical product, from design to end-of-life (sustainable materials, design optimisation, lifecycle management, noise reduction)[16].	2

Aircraft of the future

			Technological maturity (1 to 4)
	Smart avionics	Use of onboard electronic systems in aircraft integrating advanced navigation systems, new communications systems (e.g. satellite-based), automated flight control systems, adaptive systems (via AI), etc.	4
	Autonomous aircraft	Aircraft capable of flying without direct human intervention (e.g. drones) programmed to carry out specific tasks: data collection, surveillance, delivery, etc.	3
	Vertical take-off and landing aircraft	Aircraft capable of taking off, landing and moving vertically without the need for a traditional runway (e.g. VTOL, V/STOL drones, helicopters).	3
	New prototypes	Designing new types of aircraft in terms of configuration and architecture: box wing (connecting the wings), blended wing body (changing the body of the aircraft to integrate the wings with the fuselage), laminar flow (optimising the surface coating), bionic structure (adapting models, systems and biological elements derived from observing nature to solve engineering problems; e.g. "duck flight", albatross wing), pulsed detonation, struct/Truss-Braced wing (increasing the wingspan of aircraft), etc.	2

16 - Latecoère wants to switch from copper to optical on the 200 kilometres of installed cables. Benefit: higher-quality throughput and weight reduction between 1 and 3% of the aircraft's weight; Space optimisation with the use of technology to streamline cabin use according to demand; ATR offers the Cargo Flex option with the ability to reconfigure from full passengers to a freight/passenger combination by replacing four to seven rows of seats with modular containers.

Implementing these new technologies presents significant challenges for the engineering field. **Designing and integrating them into complex aircraft systems requires a methodological revolution that goes beyond simply adopting digital tools.**

We believe that advanced design and lifecycle management approaches can significantly contribute to developing tomorrow's aircraft and systems. These approaches allow for a comprehensive consideration of all system aspects, including their environmental footprint, throughout the entire lifecycle, leading to more efficient, error-free, and environmentally friendly systems.

MBSE – *Model-Based Systems Engineering*

MBSE, or Model-Based Systems Engineering, is a modelling-based discipline for all systems engineering activities (ConOps, requirements capture, operational architecture, functional architecture, V&V, etc.). MBSE models form the primary basis for the design, analysis, simulation and documentation of complex systems.

MBSE enables engineers to formalize, visualize, and simulate system and component interactions during the early lifecycle phases. By centralizing engineering data in a shared model, this approach highlights potential issues and mitigates risks associated with architectural decisions.

In Aerospace-Defense, MBSE encompasses all aspects of an aircraft, including structure, electronics, communications, and software. It provides modeling and simulation resources that are optimally suited to address the challenge of reducing carbon footprints through various means:

1. **Design optimisation:** simulating and analysing a system's energy performance and CO_2 emissions prior to implementation.

2. **Lifecycle Analysis:** modelling the entire system lifecycle, from manufacture to dismantling, to identify phases with the greatest carbon footprint impact.

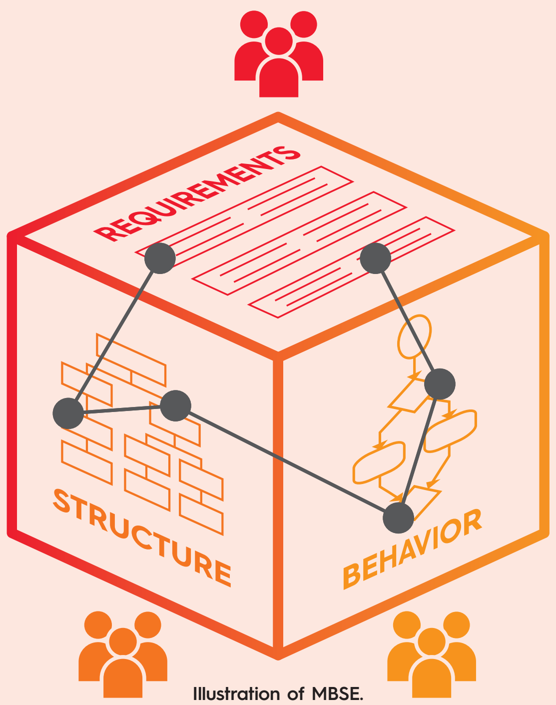


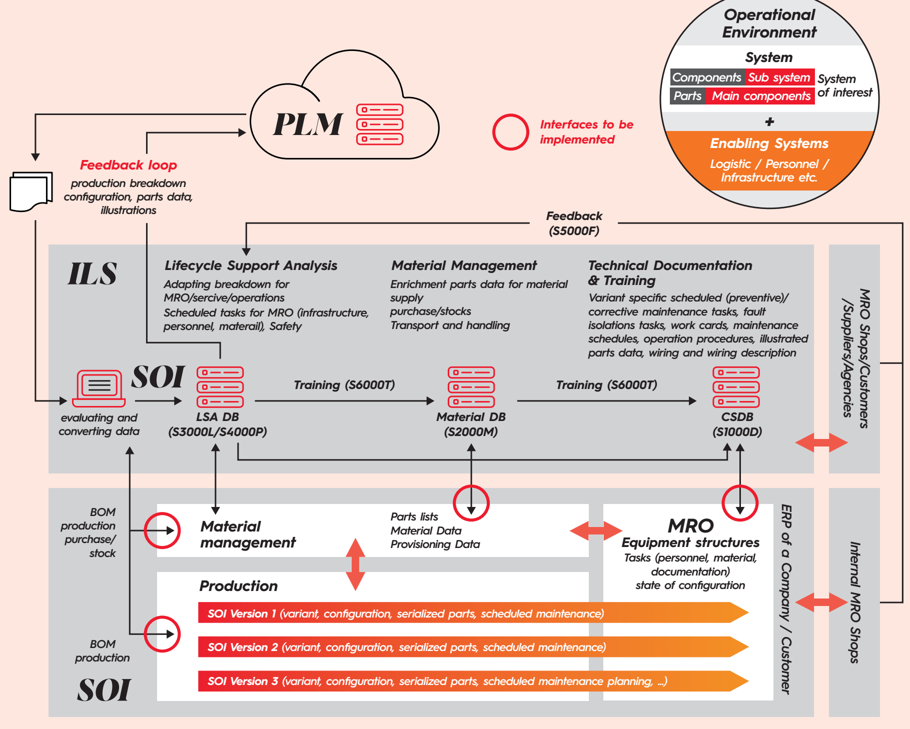
Illustration of MBSE.

SLCM – *System Life Cycle Management*

It is important to note that for most products, 70% of total ownership costs occur during the service/operation phase, while 80% of decisions are made during the conception/design phase.

System Life Cycle Management aims to holistically consider the system's entire lifecycle. This encompasses Planning, Design, Development, Commissioning, Operations, Maintenance, Upgrading and, eventually, Sustainability considerations and system scrapping and dissembling. These aspects are based on an initial concept known as the System of Interest (SOI), which all parties involved in the system's design, realization and use agree upon, including operating costs. Essentially, this method is a comprehensive approach that aligns organization, processes (standards) and information systems (digital continuity).

SLCM approach, Sopra Steria



The SLCM approach adopts the norms and standards set by the ASD (Aerospace, Security and Defence Industries Association of Europe).

Implementing these technologies require updating the regulatory framework to establish standards and support certification for new parts or assemblies. This need is addressed by the EU-funded Concerto project (Construction Of Novel CERTification MethOds and Means of Compliance for Disruptive Technologies), led by the ISAE-SUPAERO research institute. This project aims to develop new certification methods and compliance demonstration means for the three disruptive aircraft concepts identified by Clean Aviation.

The integration of new technologies, whether incremental or disruptive, requires consideration of their maintenance. This involves defining maintenance processes and new practices for aeronautical parts recyclability. For instance, research could focus on defining new standards for reusing polluted titanium or utilizing superalloys and composites in newly machined parts. This effort must prioritize the preservation of flight safety and equipment durability.

Transforming *operations and supply chain*

The current transformation facing the industry has two key characteristics:

1 - the acceleration and broad scope of necessary change;

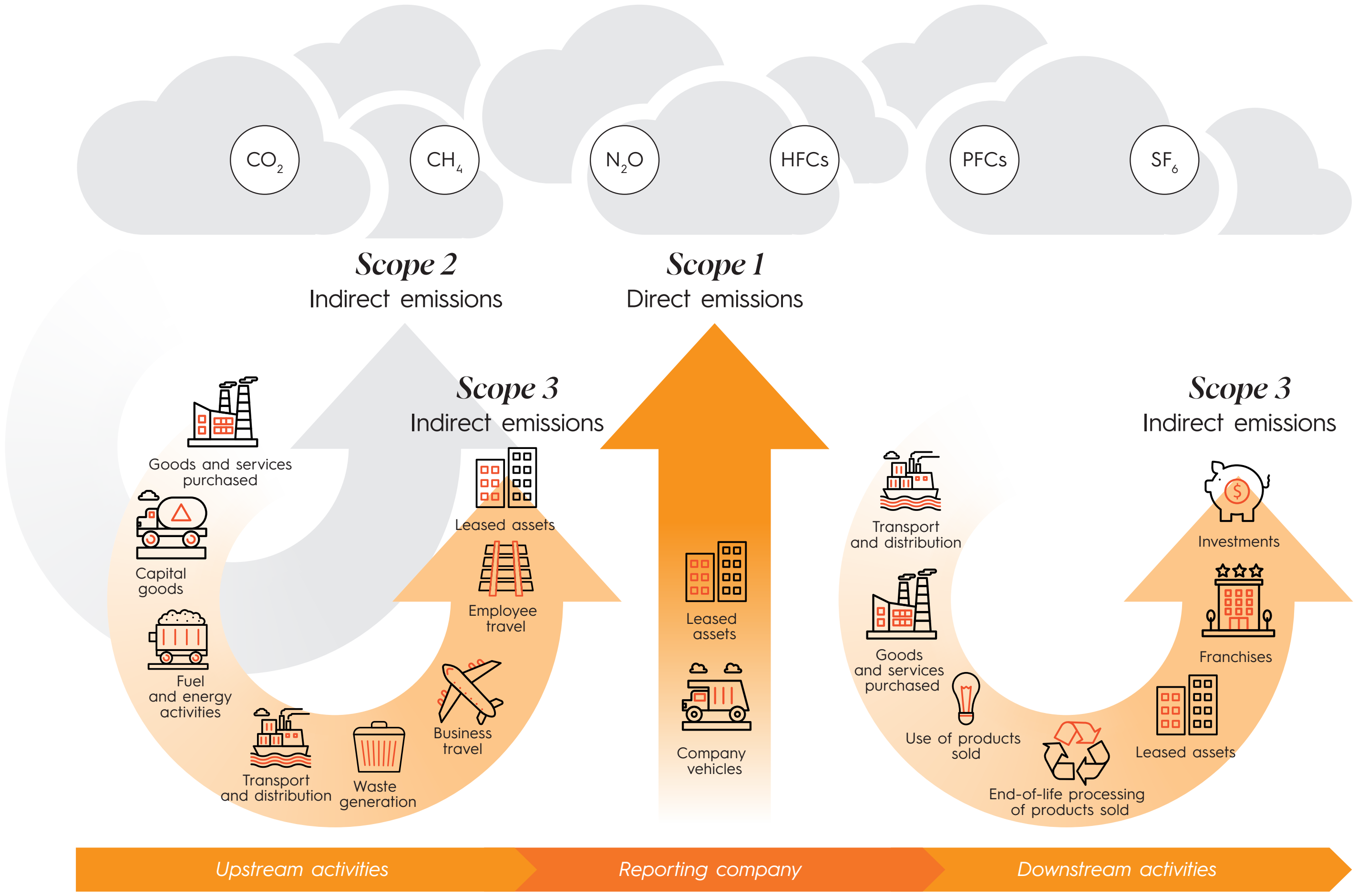
2 - the gap between the investment required and the actual benefits for the investors or stakeholders[17].

Consequently, beyond technological innovation, the industry must transform its operating models to meet emission measurement criteria.

In France, these criteria are outlined in the ISO 14064 standard, which stems from the international Carbon Disclosure Project (CDP) framework. The CDP, in turn, originated from the GHG Protocol framework created in the 1990s, which notably introduced the concept of emission scopes.

Companies across all sectors are mandated to report their emissions to an organism (ADEME in France). Starting in 2025, they will also be required to report under a more comprehensive framework, the Corporate Sustainability Reporting Directive (CSRD), based on their 2024 emissions data.

17 - Sustainability in the aerospace defence industry, KPMG (June 2023) However, as of June 2019, the Industrie du Futur program led by Space Aero and GIFAS has released 23 million euros to support around 300 SMEs in the aerospace sector towards Industry 4.0.



Source : *Greenhouse Gas Protocol: overview of GHG Protocol scopes and emissions across the value chain.*

Highly complex chains require *data sharing and collaboration between players*

The categorization of emissions into Scopes 1, 2, and 3 reveals that an industrial company's carbon footprint is heavily influenced by its supply and distribution chains. This is particularly true for system builders/integrators, such as OEMs and most tier 2 and 3 suppliers in the aerospace industry. Despite this, companies are required to declare their greenhouse gas emissions (GHG) across all three scopes. **In an aerospace supply chain, Scope 3 can easily account for 70% or 80% of the total carbon footprint.** This underscores the need for manufacturer to understand their entire chain, beyond the global reporting system that facilitates necessary adjustments.

The intricate web of interactions highlights the challenges in measuring carbon impacts at each stage of the chain. In this context, digital twins could serve as an invaluable tool, while collaboration between stakeholders could become a strategic advantage.

Consequently, the following elements are more crucial than ever: dialogue between stakeholders, information sharing, data sharing, comprehensive and detailed understanding of each product's value chain across multiple supplier tiers.

Collaborating is *a strategic decision and brings benefits.*

To reduce the carbon footprint of the Customer/Supplier value chain, actors must redesign their models by involving suppliers from the early stages of the supply phase. This can be achieved through several key strategies:

1. Encouraging supplier waste reduction, either by upgrading their own manufacturing processes, or by designing parts using innovative products or materials (eg. biodegradable), or by implementing new processes for reusing used, derived or recycled products.

2. Ensuring supplier expertise in emerging technologies and processes (electrification, hydrogen).

3. Evaluating and qualifying suppliers' sustainable supply chain policies.

4. Optimizing transport and delivery strategies for parts and equipment.

Collaboration and sharing best practices: *the example of Safran*

During their Supplier Days, manufacturers are mobilizing and raising awareness among their suppliers about the challenges and action plans required to meet CO_2 reduction commitments. For instance, in July 2022, Safran[18] hosted a Supplier Day that brought together nearly 300 representatives from the Group's main suppliers. Safran has committed to reducing its Scopes 1 and 2 emissions by 50% by 2030, compared with 2018. These include: Scope 1 - meaning direct emissions from Safran sites (e.g. gas heating, kerosene combustion in test benches), Scope 2 - indirect energy-related emissions (e.g. supply and use of electricity and heat in facilities). Notably, emissions from the Group's suppliers (scope 3) account for almost 10 times the combined emissions from scopes 1 and 2. The Supplier Day event, scheduled to be repeated in 2023, provided an opportunity to share new initiatives such as EcoAct (training platform), and Aero Excellence program for assessing suppliers' low-carbon actions.

18 - Safran gets its suppliers on board its decarbonisation path" Safran new from 07/27/2022 https://www.safran-group.com/news/safran-gets-its-suppliers-board-its-decarbonization-path-2022-07-27

Digital continuity is a must

To shorten prototyping cycles, new technologies are enabling enhanced collaboration among stakeholders through digital continuity, digital twins of products and processes and, more recently, implementation of industry-specific federated dataspaces.

Digital continuity, crucial to the aeronautics industry, aims **to link a company's multi-disciplinary processes and systems, as well as to collect, trace and share related data throughout a product's lifecycle, from design through production and use**. The digital enterprise promises to facilitate concurrent understanding of the product, industrialisation and manufacturing processes. This approach reduces risks and accelerating implementation. Companies face several challenges, including reaching consensus on data sovereignty, security, quality and valuation models for data and resources throughout the lifecycle of parts and systems, including potential second-life applications. **The Gaia-X data space initiative offers promising prospects in addressing these challenges.**

End of life: *an overlooked topic*

Aircraft end-of-life management **during the dismantling phase is a promising downstream Scope 3 lever.** With increasing pressure on natural resources, particularly metals, integrating aircraft repairability and recycling into lifecycle management is crucial. The concept of assembling new aircraft from used parts could become a reality.

The Horizon Europe SUSTAINair project launched 2021 aims to implement circular aviation, focuses on maximizing sector resource utilization, involves eleven European research organisations and industrial partners. Similarly, Aerospace Valley competitiveness cluster's call for expression19 (February 2023) focuses on end-of-life commercial aircraft and their dismantling.

The industry faces a paradox: pushing for longer aircraft use versus the trend towards shorter lifecycles driven by airlines seeking more fuel-efficient aircrafts. A part of the solution to this paradox lies **in developing a circular economy[20] compatible with future aircraft design, new technologies and environmental requirements.** The technical feasibility of recycling aerospace materials has already been illustrated: Tarmac Aerosave claims a 92% recycling rate[21]. However, challenges remain: most recovered materials are no reused in the same industry. This requires rigorous monitoring and manufacturing processes adapted to the reuse of parts, for which the current lack of traceability prevents large-scale implementation of parts reuse.

In addition to the future industrial dismantling plan, **it is also necessary to include future needs:**

- Develop methods and tools for organising and processing information on systems, parts, components and materials.
- Resolve data inconsistencies (part list, traceability) in order to improve dismantling management and to facilitate material recovery for potential use in new aircraft.

The European Union is introducing new regulatory requirements through the Digital Product Passport (DPP) initiative. This measure aims to promote circular economy practices by mandating traceability for environmental information related to products.

19 - Call for expressions of interest circular economy 2023, end-of-life commercial aircraft, Aerospace Valley.

20 - Cf. on this subject Stanford Graduate School of Business, The road toward a circular value chain.

21 - «Tarmac Aerosave : quand économie circulaire et aéronautique se donnent la main», La Tribune, 2017.

Rethinking models *to reduce the carbon footprint of products*

The product (e.g. aircraft, engine, wing, landing gear) is a crucial component in the circular economy value chain. Both the product as whole and its individual parts , significantly influence the carbon footprint throughout their use and lifespan.

Beyond research into components and processes, opportunities exist to incorporate a higher percentage of recycled materials, fluids and parts into the product. Ongoing initiatives aim to better manage the use of critical materials (e.g. recycled titanium, regolith to generate oxygen, iodine to replace xenon). IRT Saint Exupéry in collaboration with Airbus, Aubert & Duval and Safran, has launched the DéfiTitane project. This initiative build son the success of the MAMA (Metallic Advanced Material for Aeronautics) project, which validated processes that reduced titanium consumption by approximatively 30% in manufacturing critical aircraft parts, as demonstrated by initial die-forged prototypes. DéfiTitane, with a projected budget of 8 million euros over three years, serves two primary purposes:

1. Accelerating the hybridisation of conventional metallurgy technologies with 3D manufacturing techniques;
2. Establishing the groundworks for a French titanium recycling industry.

The AIR'UP project

AIR'UP is poised to become the pioneering Dismantling Information System platform, designed to digitally transform all dismantling and recycling activities in the aerospace industry. Its primary objectives are to establish a secure connection between various industry stakeholders, to facilitate the exchange of information necessary for completing eco-circularity loops and also to provide assistance in implementing end-of-life aircraft management stages.

The platform will harness Artificial Intelligence to synthesise information crucial for dismantling and recovery operations. Equipped with constrained reasoning capabilities. AIR'UP will utilize digital mock-ups of the equipment to locate and identify materials, to propose safe extraction protocols, to validate technical and economic feasibility and to monitor operations.

Additionally, AIR'UP will support training operations, monitoring and orchestration of operations and assistance through augmented reality systems.

New approaches are emerging around the "product as a service" model, aiming to regulate parts and energy consumption to optimal and to maximize the lifespan of equipment and systems. This concept is gaining maturity within aerospace manufacturers' Customer Service strategies. Notably, it is driving a reassessment of retrofit and upgrade management approaches.

Rethinking models *to reduce the carbon footprint of industrial infrastructure*

Incorporating circularity into assembly and production plants requires a review of processes and procedures to reduce waste, to minimize energy and fluids consumption or to use new 'green' alternative energies. Deploying additive manufacturing techniques[22] can optimize material consumption and reduce scrap, contrasting with traditional methods like milling, sanding or cutting. To achieve this goal, 3D manufacturing must employ bio-sourced or recycled materials.

This new manufacturing approach prompts a rethinking of factory models. The industry must adapt production tools and equipment for profitable small to medium production runs. For repair and maintenance parts, locating 3D production units close to consumption points (e.g. airports, hubs, etc.) would reduce transportation needs for part dispatch.

Production units must implement new strategies to optimise consumption of electricity, oil or water. This can be achieved by becoming prosumers[23] or by integrating green energy use.

22 - Eco-friendly 3D printing, Techniques de l'ingénieur, March 2018.

23 - Combination of "producer" and "consumer".

Transforming operations and supply chain

Measuring and simulating *the carbon footprint at every stage*

The air transport sector's global transformation relies on complex, cross-sectoral scenarios, necessitating information sharing. Tools like AeroMAPS[24] (Multidisciplinary Assessment of Prospective Scenarios for Air Transport) or Cascade[25] (Collaborative Analytics and Simulation for the Commercial Aviation Ecosystem) have been developed to promote alignment among industry players, to foster common understanding and to facilitate the emergence of macro-strategies for decarbonisation.

At the industrial level, it's becoming crucial to integrate, from the initial production plan, an optimal balance calculation between physical flows, environmental impact, industrial performance (quality, milestones) and financial performance.

For instance, SAF production may remain under-capacity in the near future, leading to inter-sector competition and high prices. Integrating these factors into S&OP (sales & operations planning) processes is vital for decision-making. Prospective scenarios could include: Business as usual, Carbon reduction first or hybrid approaches.

The challenge lies in conducting an exhaustive, comparative, continuous and multi-criteria analysis considering CO_2 emissions, other GHGs, resource consumption, noise and soil pollution.

The goal is to strike a cost/benefit balance regarding the market risks and, the public concerns and institutional requirements. Modelling the production system (e.g. as a digital twin), will enable the simulation of industrial, economic and environmental developments and the optimisation of physical flows and their carbon impact.

24 - Open-source modelling tool for transition scenarios for the aviation sector created by ISAE-SUPAERO.

25 - Designed by Boeing, the Cascade Climate Impact Model is a tool for modelling the main aviation strategies for reducing greenhouse gas emissions.

Operations: *a wellspring of opportunities*

According to the above-mentioned studies, enhancing aircraft operations is a lever for reducing the aviation industry carbon's footprint. The potential contribution of these improvements to the overall decarbonization effort ranges from 3% (as estimated by IATA) to 7% (according to Waypoint 2050). This includes airport infrastructure itself (ground operations, equipments, and management), aircraft operations (maintenance, operation and associated equipment) and air navigation (flight and space management, flight and trajectory optimisation).

Airport *infrastructure and equipment*

The French Civil Aviation Authority (DGAC) is prioritizing aircraft performance improvement, while acknowledging the need for concurrent energy infrastructure development. Most of these initiatives target short and medium-term goals, whereas decarbonised energy production infrastructure (e.g. SAF, e-fuel, hydrogen) demands significantly more extensive efforts.

Consequently, it is crucial to optimise existing ground infrastructure to maximise current infrastructure utilization and to prepare for the transition to new sustainable energy solutions. Many airports and airlines are already implementing various ground facility optimization strategies, including:

Harnessing renewable energy sources for the airport operations (buildings, car parks and equipment): solar panels, wind power, geothermal energy...

Retrofitting existing infrastructures, terminals, hangards for energy efficiency: LED lighting, modern HVAC systems, adjusted operating temperatures, building management systems implementation...

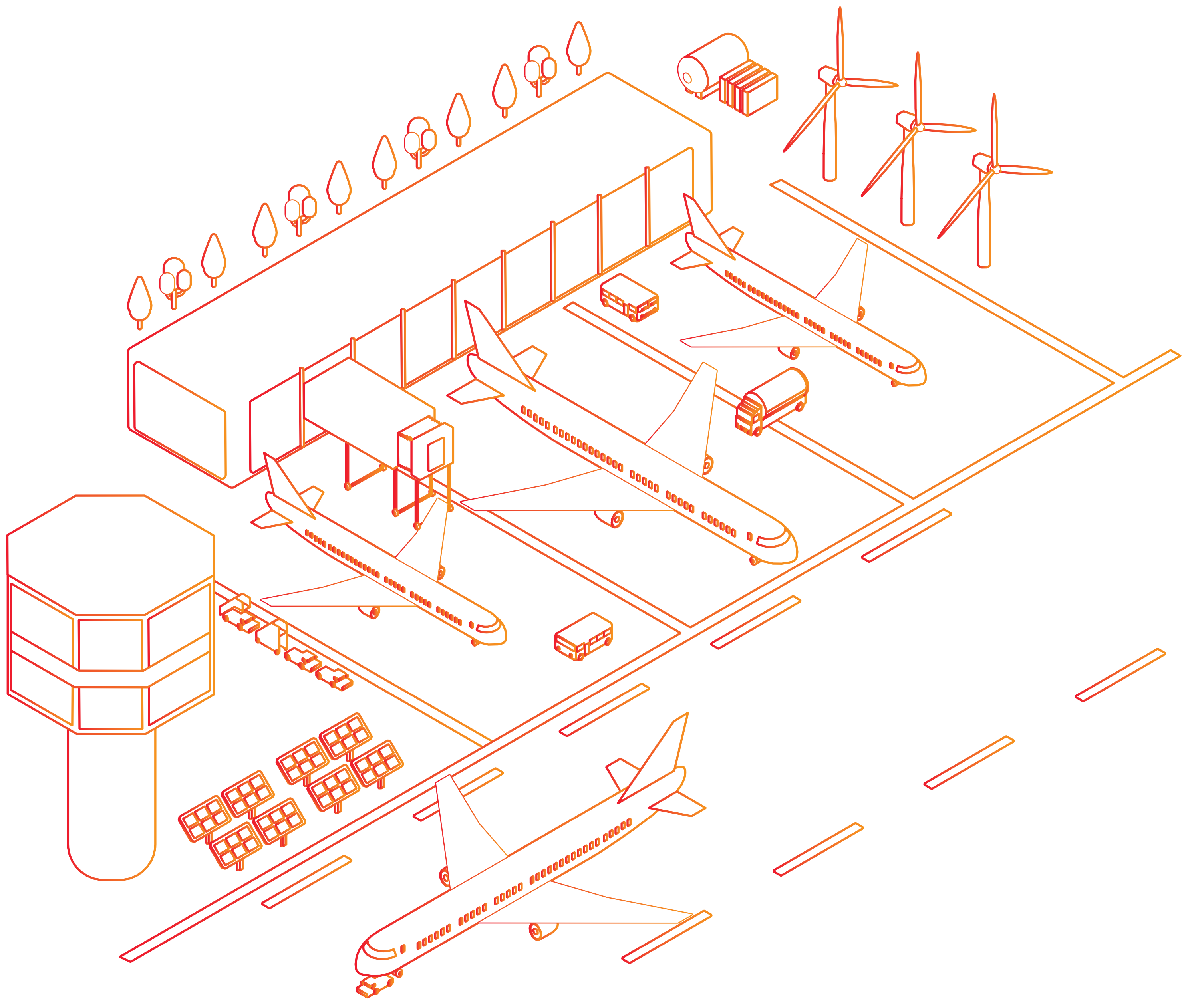
Constructing new infrastructure to contemporary environmental standards.

Replacing conventional ground equipment (baggage transport, buses, tractors/push backs) on aircraft with sustainable alternatives such as electric, hybrid or hydrogen-powered options.

Implementing sustainable ground transport options: public transport, electric shuttles (shuttle trains) - and recharging systems. These measures can significantly reduce the carbon footprint of passengers and employees.

Carbon Management strategies include offsetting or carbon capture systems: an airport can support offsite carbon reduction projects and invest in carbon capture and storage to offset operational emissions.

The implementation of a system such as Environmental Management Systems (EMS) offers comprehensive functionalities for the identification and the calculation of operational carbon footprint, the management of action plans, the support of staff training and the compliance with environmental standards, such as EN/ISO 14001 or EMAS (Eco-Management and Audit Scheme). By implementing these practices as part of medium-term planning, airports can significantly reduce their carbon footprint across the Scopes 1, 2 and 3.



The need to consider *ground operations*

Ground cooling systems: the implementation of preconditioning systems for cooling or heating aircraft cabins aims to reduce or eliminate the use of aircraft air conditioning powered by auxiliary power units (APU). This approach significantly decreases fuel consumption and emissions during ground operations.

EGTS (Electric Green Taxiing, System) technology allows aircraft to taxi and reverse without using their main engines or requiring a pushback tractor. In some cases, it may involve using only a limited number of engines for taxiing. The Safran group estimates that this system can reduce an aircraft's annual fuel consumption by approximately 4%.

Optimized Ground Traffic Management: Improved coordination between airlines and airport operators enables more efficient management of ground traffic, reducing waiting times and unnecessary movements. Major French airports, including Paris Charles de Gaulle, Orly, Lyon, and Nice, have implemented numerous initiatives to minimize pre-takeoff waiting times by optimizing the timing of aircraft leaving their parking positions.

Aircraft maintenance, a quasi-industrial activity, can adopt many best practices for decarbonization. Particular attention must be paid to supply chain operations and planning. Improving collaboration and coordination among stakeholders in estimating needs, enhancing planning, and increasing responsiveness in interventions can help minimize aircraft downtime and waiting times.

Implementing Smart Maintenance strategies based on detailed data analysis, anticipation of potential failures (predictive maintenance), innovative characterization resources, non-destructive testing, digitized procedures can optimize resources. These approaches should be precisely synchronized with spare parts logistics involved in the maintenance process.

Utilizing 3D printing technology to produce spare parts as close as possible to where aircraft are parked, reducing carbon-intensive transport of these components. Full-scale 3D parts production centers are emerging, with an increasing number of critical and "hot" parts (those functioning inside the engines) now manufacturable using 3D printing techniques.

Assessing the carbon footprint of customer service to identify alternative, more sustainable options. Optimizing Maintenance, Repair, and Overhaul (MRO) practices through lean management approaches, of which intrinsic "just-as-needed" philosophy is well-suited to this context.

Optimising *flights operations*

In this area, **digitization serves as a critical lever, provided that principles of coordination and cooperation are established at national and regulatory levels to prevent procedural "disruptions.".**

Trajectory optimization: solutions such as PureFlyt from Thales calculate trajectories and make continuous, accurate predictions based on flight parameters and external factors like weather. These systems optimize fuel consumption in real-time, with reported gains of approximately 3% to 4% compared to previous technologies.

Updating procedures and digital tools for 'Green' piloting: flight manuals are being revised to adapt piloting across various ground and in-flight phases to be more fuel-efficient, known as green operating procedures. In 2020, Air France, along with 42 other airlines, adopted the Skybreathe ecopilot solution from the start-up OpenAirlines for its Transavia airline. This system is based on systematic collection of fleet flight data and employs AI/machine learning algorithms to identify configurations and opportunities for fuel savings of up to 5%.

Another innovative concept currently under testing is **formation flying,** where multiple aircraft fly in a single file during a portion of their route. This technique aims to reduce fuel consumption by approximately 5% for long-haul aircraft by leveraging the wake effect and thus reducing turbulences.

Finally, studies have investigated the possibility of **modifying flight plans to reduce the formation of condensation trails** (contrails) while minimizing the associated increase in fuel consumption. This proposal shown promise but requires further research and a deeper understanding of the physico-chemical phenomena responsible for high-altitude cloud formation. The use cases related to contrails are of significant interest, as their potential impact on climate change could be as substantial as that of GHG emissions.

Adapting Air Traffic Control Methods to new ways to fly. The Continuous Descent Approach (CDO), often described as a 'gliding' approach, emerged nearly 15 years ago, with early publications by the ICAO and SESAR. Over the years, several projects, primarily under the SESAR program, have demonstrated its feasibility and confirmed the expected benefits in terms of fuel consumption, noise reduction and profitability. The CDO concept, now more mature, is ready for widespread deployment.

The Dyncat project, completed in 2022 with Swiss Air Lines' participation, not only reaffirmed the well-known benefits of CDO but also revealed that these advantages could be partially achieved simply by providing pilots with the "indication to-go" distance information from ATCO (Air Traffic Controllers).

While research continues to explore new avenues, such as the ADS-C with the Adsencio project and X-stream trials the industrialisation of change management will play a crucial role in deploying continuous descent management. This implementation has the potential to reduce the carbon impact of approaches by 10%.

Optimising traffic and defragmenting *airspace*

Air traffic optimization is one of the most potent tools for reducing aviation's environmental impact. It demands global coordination across major airspaces.

In France, the 4-Flight program for area control centers (ACC) and the **SESAR project in Europe** are contributing to the Single European Sky (SES) initiative. These projects address new challenges such as traffic growth, which requires the creation of more airspace, improved overflight management, and the need for greater anticipation and agility. These also promote collaboration between air traffic = management (ATM) organisations.

The combined impact of these projects within the SES framework could reduce CO_2 emissions by approximately 10%. Specifically, the SESAR project, which aims to modernize air traffic control tools, project savings of 1.7 million metric tons of CO2 and 540,000 metric tons of jet fuel by 2030.

A key proposal is the establishment of a "European Tactical Hypervisor". While Eurocontrol plans air operations, the tactical management of these operations remains fragmented, with responsibility distributed among individual governments and various players in the aviation value chain.

The current aerospace network lacks an overarching tactical vision of all aviation resources and fails to effectively manage resource conflicts across different capacities, including:

- Airspace network capacity;
- Airlines' aircraft network capacity, including associated staffing (pilots, cabin crew, ground staff),
- Airport resource capacity and associated.

The volume of aircraft (10,000 per day in France) is relatively low compared to other transportation modes. For context, the Swiss Federal Railways (SFF) tactical operators manages 10,000 trains daily, optimizing network capacity, trains, locomotives and crews for multiple companies.

A primary action could be to authorize departures only when a landing slot is guaranteed available. This is the goal of Collaborative Decision Making (CDM) systems integrating Arrival Manager (AMAN) and Departure Manager (DMAN), which synchronize arrivals and departures.

While the major European airports are required to coordinate aircraft flows using AMAN/DMAN systems, this concept has yet to be rolled out across the entire airport network. A poorly coordinated second-tier airport can impact resources throughout the network, leading to cascading delays. This underlines the importance of change management in measuring optimal tactical conditions for flight operations, airports and airlines.

The fragmentation of operations (Airport, Airlines, Airspace) among different stakeholders implies the sharing of planning and tactical data to create an optimal European tactical network. This concept forms the basis of the proposed European Tactical Hypervisor, or EU Aeronautic Operation Metaverse.

Conclusion

Substantial investment to Reinvent the Industry

The Aerospace sector has committed globally to decarbonising and transforming its operations. This initiative spans the entire value chain, targeting multiple areas: fleet renewal, alternative fuels, aircraft design, supply chain optimization, manufacturing processes, operational improvements, maintenance strategies and infrastructure development.

The industry and government institutions have invested significant financial resources in this decarbonization initiative. IATA estimates the decarbonization process will cost $5 trillion by 2050. The scale of the challenge is immense. It promises new business models based on collaboration, information sharing and, of course, innovation in products, processes and tools. In fact, digital transformation is proving indispensable to achieving these goals.

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