Research paths for a viable air transport system in 2050

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THE FRENCH AEROSPACE LAB

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Foreword

This study was carried out by Onera's "Département Prospective Aérospatiale", and was co-funded by Onera and EREA (European Research Establishments in Aeronautics).

Onera largely drew on its experience as coordinator of various major projects, including the following:

> **IFATS** (Innovative Future Air Transport System), concerning the advanced automation of the air transport system,
> **4DCo-GC** (4D Contract – Guidance & Control), on the use of 4D contracts to enhance air traffic,
> **PPlane** (Personal Plane) for a personal air transport system.

The study was written by scientists in Onera's Long-term Design and Systems Integration department:

> **Bruno Lamiscarre**, deputy director, "Air Transport System" advisor, and director of the IESTA program ("air transport system evaluation infrastructure"),
> **Jean Hermetz**, head of the Aeronautical Systems research unit,
> **Claude Le Tallec**, Drone Systems advisor and coordinator of the IFATS and PPlane projects,
> **Muriel Brunet**, Clean Sky Technology Evaluator project manager,
> **Antoine Joulia**, research engineer, coordinator of the 4DCo-CG project,
> **Thomas Chaboud**, research engineer.

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Contents

The future of any leading-edge sector depends on decisions made decades earlier in research centers and laboratories. In key technology areas such as energy, materials, design, onboard systems, infrastructure and environmental protection, making correct and timely decisions is crucial. The entire air traffic environment will have changed significantly by 2050. But to what degree will it actually change, and what resources will it need to support these changes? Whether the dominant scenario turns out to be unlimited development, drastic regulation, the virtual disappearance of the sector, or a combination of all three, the enabling technologies will undoubtedly not be the same. ■

Scenarios and technology options

Several factors will have a considerable short-term impact on our society, including the depletion of oil resources, global warming and growing equality gaps worldwide. In fact, their effects are already perceptible. The air transport sector and its stakeholders are especially vulnerable to these factors, not only because the sector consumes resources and generates polluting emissions, but because its very raison d'être is in fact to support national and international travel and trade.

We must therefore ask certain vital questions, starting now. Will mass air travel still exist in 40 years? Will passengers still be boarding conventional, but ever-larger airplanes, or will they be in brand-new aerial vehicles based on disruptive technologies? Will aviation offer an alternative to private cars? And in that case how will we define air travel? Will we have made the transition from fossil to alternative fuels? Will we have invested in the air traffic control systems needed to unclog our airports, or will we run into the limits of a system that is already saturated?

These are not just theoretical questions. In fact, they clearly reflect how our society sees its future, and how it mobilizes its research resources. There are already paths indicating how we can shape a different world, but one in which air transport will still play a role. Moving forward will depend on the technological and organizational decisions that we must make in the near future. We have therefore sought to imagine the role of air transport in 2050, based on the four scenarios defined by the Consave[1] study, and provide a comprehensive picture to support the decision-making process. We have used these contexts and backgrounds to build an organizational substrate based on pertinent technology options, capable of offering a comprehensive, "system" vision.

[1] A study carried out from September 2002 to July 2005 by a consortium of DLH, DLR, NLR, QinetiQ, IIASA, MVA and Airbus, on behalf of the European Union (http://www.dlr.de/consave/index.html).

Unlimited Skies

Unlimited Skies

Explosive growth, automated control systems

The first scenario is called Unlimited Skies (ULS). It represents a world that is not fundamentally constrained by energy availability. This doesn't mean that people don't need to save energy, but that the world is not governed by shortages. In consequence, aviation undergoes explosive growth, with the development of many different types of aircraft.

Conventional large commercial jets, already very close to the optimum, have decreased weight by calling on advances in materials. This means that aircraft can carry more payload, increasing their profitability. Super-jumbo jets with 1,000 seats, but about the same size as an Airbus A380, are in widespread use. Existing airports are able to handle these super-jumbos without any problem. Advanced aerodynamic design has reduced drag, thus reducing their fuel burn – an extremely important point since fossil-based fuels are increasingly expensive. In fact, that is one of the key factors in this scenario.

There is also a role for alternative concepts such as the Blended Wing Body (BWB), an evolution of the old "flying wing" lifting body, because of the enhanced efficiency of this type of design. The development of artificial stabilization (computerized flight controls) has removed the major drawback of this configuration, which was the difficulty of combining controllability and performance. This applies even more because boundary layer air control devices are now capable of generating extra lift, while diminishing the aerodynamic penalty. The upshot is that we will be able to exploit the advantages of this concept, in particular increasing carrying capacity without decreasing efficiency. We can therefore design large-capacity aircraft with reasonable outer dimensions, by making widespread use of composite materials offering high specific strength. We can now fully control the design and qualification of these materials, which are partially recyclable, as well as their behavior over time due to integrated health monitoring systems.

Blended Wing Body (BWB)

The BWB is an extension of the well-known flying wing concept, in that the fuselage plays a significant role in providing lift. Both wings and the tail assembly are merely stumps. This means that the volume left for passengers and freight is maximized. It also provides the space needed to "bury" the engines in the airframe, which significantly masks any noise generated. However, this configuration does not only offer advantages. Boarding and evacuating passengers is more complex, and they do not necessarily enjoy maximum comfort. Passengers placed near the center of the structure will not have any external visibility, while those seated farthest away from the centerline may be disturbed by the aircraft's rolling motion.

Buried engines

As the term implies, a configuration that "buries" the engines in the airframe. This concept is particularly suited to a Blended Wing Body, or BWB type aircraft, which offers considerable internal volume.

Because of their large available volume, Blended Wing Body aircraft will also enable the use of certain innovative propulsion concepts, such as buried engines, in which the engines are placed inside the structure. This has the dual advantage of reduced drag (and therefore lower fuel burn) and a smaller acoustic footprint. These advantages are all the more important since traffic is growing by leaps and bounds, and we have to address the problem of disturbances, especially around airports.

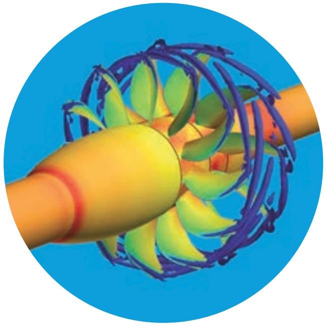
Another innovative technology is the distributed propulsion configuration, which would increase overall energy efficiency, while at the same time decreasing acoustic impact. The idea here is to distribute the propulsive effect on the airframe, and therefore "fill in" the wake to prevent boundary layer separation. This solution may also result in decoupling electrical generation and the propulsive effect. Drag reduction is also reflected in the infinite aspect ratio of the rhombohedral wing; the structural rigidity inherent in this form combined with the use of modern materials would reduce weight. We will also see tiltrotors, combining vertical takeoff and landing with conventional lift for forward flight. All of these aircraft use internal combustion engines, and one of the top research objectives is to reduce their emissions.

Likewise, the use of propellers on either piston or turbine-powered planes, instead of jet engines, cuts fuel consumption on certain types of routes. This is not necessarily synonymous with reducing speed. For example, the Contra-Rotating Open Rotor engine, or CROR, which involves even greater airflow than a conventional layout and generates an exhaust nearly as fast as cruise airspeed, provides excellent performance. However, because these contra-rotating blades are unshrouded, noise is still significant in the low-frequency band. But they still generate economic savings sufficient to support the massive use of this type of engine in the Unlimited Skies concept.

Infinite aspect ratio (rhombohedral wing)

Unmanned tiltrotor

CROR (Contra-Rotating Open Rotor)



Airport used as a hub

The airport environment in this scenario is very similar to the current situation, in which hub and spoke networks operate alongside a network of secondary airports supporting point-to-point service, for example to link secondary cities without transferring via capital cities. The number of airports is not significantly larger. But since the number of aircraft in service is booming, air traffic control has to be entirely revamped to avoid saturation. With only a few exceptions, the notion of conventional piloting will be replaced by a “full automation” concept, along with the “4D contract”. In constant contact with a complete ground control and command system, cockpit-less aircraft automatically follow flight paths adjusted to avoid major cities and decrease the distance flown for lower fuel consumption, without waiting, delays or conflicts. These flight paths include descent profiles into approach zones with significant glide slopes, flown with engines at idle to limit consumption and noise.

Full automation

Automation means that a system depends only marginally on human intervention in real time. All procedures are implemented by automated systems, which merge the functions of pilots and ground controllers into a new function carried out on the ground, whose precise scope must still be defined. In this case, each aircraft, either linked by a 4D contract with the control authority, or even in free flight, is controlled by an automated system. It has collaborative capabilities in a local loop, enabling it to resolve local conflicts; i.e., those limited to the immediate section of the sky where it is at any given moment. This would enable it, for example, to manage unforeseen situations, particularly in cases where the communications links with the ground are degraded. In this case, aircraft that momentarily no longer receive instructions from the system, can work out how to avoid colliding with each other, and continue their flight. Full automation does not mean that people are totally out of the loop. There will no longer be pilots in commercial airplanes, of course, but an airline representative will have onboard authority (an evolution from the traditional captain on the flight deck). Likewise, on the ground, while air traffic control is handled by the system, this system assigns flight supervision to ground captains, who can strategically modify certain parts of the flight path if needed, such as choosing a diversionary airport, changing the approach, etc. For a given flight, there may be as many ground captains as there are ground control centers under the airplane’s route.

Hub & Spoke / Point-to-Point

These are the two basic ways of organizing service between airports as part of an overall air transport system. As indicated by its name, the Hub & Spoke system comprises a major airport, or hub, linked by spokes to smaller, regional airports, which funnel passengers to the hub. Long-haul flights leave from the hub to other hubs.
The Point-to-Point network can be summarized as a set of regional airports, in which planes fly directly between these points

In practice, actual networks are most often a combination of the two concepts. A Point-to-Point system would have a larger number of flights for the same number of passengers, along with shorter flights and smaller aircraft. It is also less vulnerable (in terms of technical failures, climate and safety), and has fewer constraints in terms of control capabilities. From the economic standpoint, the Point-to-Point network offers advantages for a segmented market (with its regional airlines and mini-hubs). However, for major airlines, it implies more complicated, more costly logistics.

In general, aviation is less dependent on other transport modes in this type of organization, because it is less integrated in an overall modular (or multimodal) design. A Point-to-Point organization would be necessary with Personal Air Transport (PAT) vehicles, that may exist in the ULS scenario. On the contrary, major hubs obviously demand very high-capacity airport complexes, in terms of runways, gates and terminals, as well as approach ATC (Air Traffic Control). For instance, air traffic growth in London is hindered by the small size of the five local airports, which already cause delays and waits.

The 4D contract incorporates the notion of time in addition to the usual three physical dimensions. Aircraft that are automatically guided along their entire flight path follow a strict schedule to be at predefined waypoints at given times. This is designed to optimize aircraft spacing (in order to further reduce wake vortices, already minimized by active aerodynamic devices in both the lead and trailing aircraft), and also helps decrease the width of the air corridors reserved for these aircraft. The air traffic control system, operated and updated in real time, can therefore make use of the airspace before and after the passage of the aircraft. In case of an event that disturbs this process, such as weather conditions that make the initial route unusable, or technical incidents, a new “contract” between plane and system is negotiated in real time, enabling the plane to take a safe new route, i.e., one that avoids conflicts with other traffic. Aircraft also communicate among each other and, if an immediate change in the trajectory is necessary (due to an engine failure for instance), they are capable of locally negotiating temporary “contracts”, enabling them to take a new conflict-free flight path.

4D contract

A 4D contract refers to a precise and negotiated scheduling of flights (prior to the flight, as well as en route in real time), along with rigorous tracking of flight paths and times at each waypoint. This is all designed to develop itineraries that avoid conflicts between airplanes, limiting downtime and maximizing the use of airspace assigned to air traffic. It also allows placing more aircraft in the sky without the risk of saturation, using optimized, complex flight paths that will save fuel, limit emissions and reduce noise. “4D” means that tracking is done not only in the three dimensions of space, but also in time. In practice, each aircraft negotiates with ATC a 4D flight plan, for which it then “signs” a contract with the system. As long as the aircraft does not signal anything out of the ordinary, the control authority is assured that the aircraft will respect its contract. The aircraft itself is assured by ATC that no conflict will occur. The situation can change in real time in case of an incident, following which a new contract is negotiated and applied. Rescheduling in real time obviously presumes that air-to-air and air-to-ground links will always be reliable and available (cooperative communications capabilities between all aircraft).

A 4D contract can only be considered feasible within the scope of a redesigned traffic management system, based on the full automation concept. In effect a controller could no more verbally express an instruction in the 4D contract, than a pilot could manually enter the instruction in his or her FMS. Excluding the purely technological aspects, the main obstacle to the 4D contract is its acceptance by the various professional associations involved, in particular pilots and air traffic controllers. Adopting this concept also assumes that airlines agree to no longer choose their routes and flight times according to their own interests, but rather negotiate with the system to determine slots – and the system would have final decision authority. In this case, traffic control is in fact the top priority, either to avoid saturation, or to limit the disturbances it causes, all while ensuring the highest possible level of safety.

Continuous descent, engines at idle

Within the scope of the 4D contract, especially as used in the Regulatory Push & Pull (RPP) scenario, air traffic must limit environmental impact as much as possible, particularly gaseous emissions and noise. One way of meeting this dual objective is for aircraft to use continuous descent arrivals, with their engines throttled back to idle. A continuous descent towards the final approach zone and the airfield limits – or even eliminates – the time previously spent at low speed and low altitude in a stair-step flight path, situations where jet engines are both fuel-hungry and noisy. Furthermore, if this procedure is applied within the scope of 4D contracts, it would drastically reduce the airspace volume assigned to this phase of flight, which would in turn unclog airports and speed up traffic, eliminate many waiting periods, etc. Aircraft are in the air for shorter periods, thus reducing noise around airports, especially since with the engines at idle, approaches generate much less noise. In short, this is a win-win situation. The only drawback is that it is very difficult for a pilot to carry out this type of descent while fully complying with the terms of the 4D contract, under any conditions of wind, temperature, etc. Mastering a continuous descent with engines at idle depends on integrating the aircraft’s weight in real time, along with atmospheric conditions, and applying a complex trajectory without allowing oneself the liberty to use a possible go-around (if not, what good would the concept be?). Therefore, this type of approach, linked to the 4D contract concept, is only possible in the case of full automation, because a human pilot would be unable to manage so many variables at once, every time, without risking an error.

Given the complexity and quantity of variables involved, which over-saturate human capabilities, this type of air traffic management can only be handled by a computerized system. Aircraft still carry passengers, but no longer have a pilot aboard. The pilot's role has disappeared with the maturity of the automated control system. However, people are still in the loop through two distinct functions: a supervisor in the airplane (successor to the captain, who represents the airline and maintains onboard authority); and a ground captain (transition of the controller's role to a supervisor tasked with managing emergency situations not provided for in the system). The ground captain can make strategic decisions (as opposed to tactical, local actions, such as the real-time control of an aircraft), insofar as human reaction time is compatible with the type of decision needed. Typical situations include the choice of routes, types of approach, or choosing an alternate destination in case of diversions. For a given aircraft during a flight, this role can be shared by as many ground captains as there are ground control centers along the route.

The concept of "full automation" is diametrically opposed to that of "free flight", in which airlines are free to choose their routes to make optimum use of the airspace in their own interest. In the case of full automation, the notion of a comprehensive system is predominant, and all players are subservient to this system. This presumes that airlines have previously negotiated their departure and destination points with the air traffic control authority, as well as the time slots they want to offer their passengers. The system is in charge of integrating all these elements in the general traffic pattern, first in terms of planning, then in real time when the plane departs (allocation of a takeoff slot), and then en route. Automated piloting concerns not only commercial transport, but also business trips and Personal Air Transport. The PAT is a very-short or vertical takeoff and landing aircraft, whose large-scale development will require a major breakthrough in terms of lift and propulsion. It could also be a helicopter or a tiltrotor. In any of these cases, the PAT would be a private vehicle like a car, except that its "pilot" would simply enter the departure and arrival points, and perhaps several waypoints between the two.

IFATS

A long-haul jetliner without a human pilot aboard

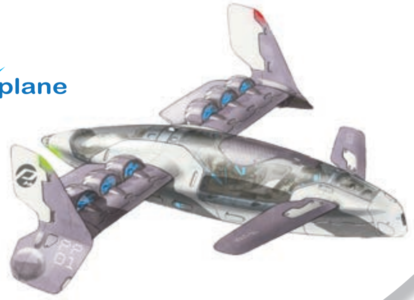
Free flight

The concept of free flight does not mean that flights are free of all air traffic control authority. It is in fact perfectly manageable within the scope of a system based on full automation. "Free flight" as used here is just in opposition to a 4D contract. Operators (airlines, aerial services firms, private owners, etc.) can choose their flight paths and time slots without these being regulated. Drones could very well fly on a free flight basis.

PAT – Personal Air Transport

PAT is the aerial version of the private car. It also represents a complete range of vehicles, from single-seater to the equivalent of a minibus. The major difference is that the notion of "driving" is eliminated completely, replaced by full automation type management. Occupants merely choose a destination, and perhaps several waypoints.

pplane



Civil and military drones would also be subject to this full automation system. Their flight paths (“loitering” surveillance circuits for example) are compatible with the 4D contract concept. The remaining categories include military, emergency and light aircraft, which are generally manned. In the case of military aircraft, as for police, medical, fire-fighting and similar missions, flight paths are requisitioned on demand (although with major constraints, since business concerns generally take precedence in this scenario), and Air Traffic Control (ATC) “clears the airspace” the time needed for a fighter patrol or emergency medical helicopter to pass. Real-time control minimizes the impact of this type of disturbance. So there are no longer any airspaces strictly reserved for military flights, as we see today.

Concerning light aviation (gliders, microlights, etc.), this must remain under pilot control, provided that these flights can be integrated in the rest of the automated traffic. Most of these aircraft use electric propulsion, and benefit from the ongoing improvements in this type of motor, tending towards increased specific power and lighter energy storage systems, taking advantage of technology developments in other sectors, particularly the auto industry. These aircraft remain very small and light. They operate on a cooperative basis, sending their position to the central system and to other aircraft in real time. Furthermore, their pilots have a 3D display (such as a head-up display) of the surrounding sky, using color coding to show what areas are free, prohibited (because they are occupied at a given moment), or if the area will be prohibited within a given period of time. This allows them to integrate the system naturally and smoothly.

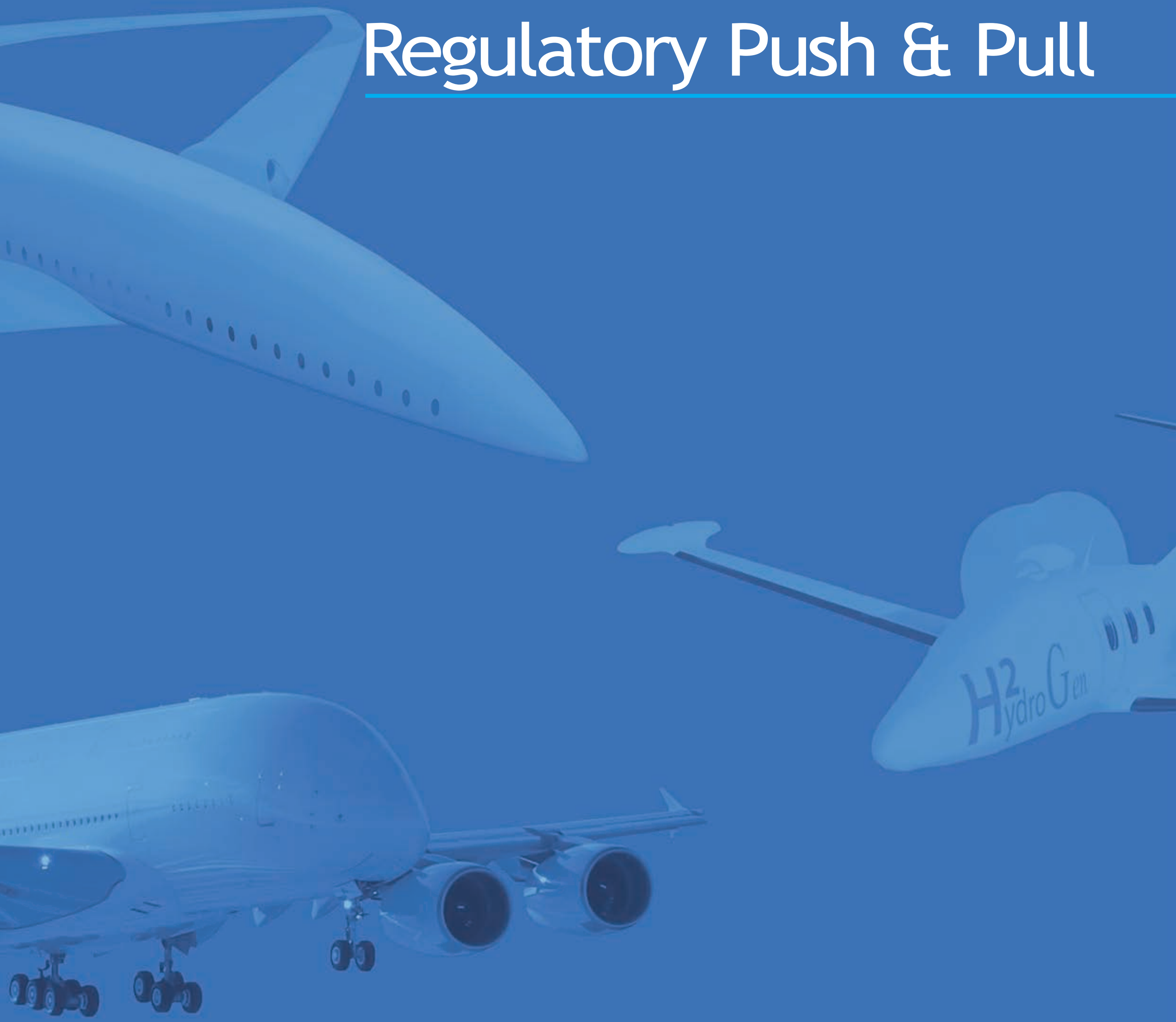
Technology choices

The cornerstone of Unlimited Skies is the combination of full automation and the 4D contract, the only way to prevent the saturation of growing air traffic. This goes hand in hand with the development of “green” procedures, designed to limit impact on the environment and surrounding populations. Since the focus is on growing the aviation business, it is also essential, in a world where energy is expensive, to develop solutions that reduce fuel consumption and make air transport more cost-effective. From this perspective, we have to emphasize revolutionary aircraft concepts (flying wings in particular) and lightweight materials. The PAT is also an option that should be considered very seriously, since it will help shift some traffic from our jammed roads to individual aerial vehicles.

Our recommendations

Efforts concerning this scenario should primarily focus on the full automation concept; as for the 4D contract, the technology involved is relatively advanced. Even though the underlying organizational strategy requires more work, a number of technological building blocks are already available. Implementing the concept is only a question of financial resources, political will and social acceptability. The revolutionary aircraft concepts and configurations (BWB included), already well advanced in terms of Research & Development, also require an effort on the production level. At the same time, we have to maintain broad-based research on lightweight materials, green procedures and the use of electrical propulsion techniques from the auto industry. However, for Personal Air Transport (PAT), we are starting from scratch.

Regulatory Push & Pull



Regulatory Push & Pull

Regulations to benefit a comprehensive environmental protection approach

The second scenario, dubbed Regulatory Push & Pull, or RPP, shares the “full automation” and “4D contract” concepts with Unlimited Skies (ULS). But whereas in the ULS scenario, these concepts were used to smooth out booming traffic growth, this concern no longer has the same crucial character in the case of RPP. This is quite simply because, with development being largely limited by an array of regulations, we don’t run the same risk of extreme saturation. The world illustrated by this scenario in fact places far more emphasis on the public interest, and is more concerned with its long-term viability and conscious of its fragility, due mainly to a series of heavy constraints. These constraints are primarily in terms of energy (both the cost and availability of fossil fuels becomes a deterrent) and the environment. This is a world dominated by electricity, largely produced by nuclear plants, but also by wind and solar power, and any other technology using a natural resource in ecological fashion.

We still face the issue of transport regulations, but it is now considered from the angle of a comprehensive, “system” approach: the only one that allows us to achieve an optimum tradeoff between all factors leading to the best specific fuel consumption. There are two main types of pollution: emissions and noise. From this perspective, the automation of air traffic (full automation and 4D contract) is tasked with guaranteeing the systematic adoption of green procedures, including anti-noise approach profiles and flight paths, engines at full idle without go-arounds. It isn’t easy for pilots to comply with all these conditions under highly variable weather conditions, especially in terms of wind. That partly explains why a large majority of aircraft do not use these procedures. They are therefore subject to very strict flight path instructions, issued by the comprehensive system. This system minimizes environmental impact by using refined, real-time calculations of glide slopes adapted to each aircraft according to its weight at any given moment. Likewise, the automation of flight enables a vertical shift in all traffic, depending on atmospheric conditions (humidity, temperature), to remove traffic from the altitudes favoring the formation of contrails; since these trails are clouds of ice particles, they act as a screen to terrestrial radiation, thus contributing to the greenhouse effect and global warming.

Contrails

A "green" airport

As in the case of the ULS scenario, this regulation excludes the contrary concept, free flight, which can only be envisaged within a context involving the absence of environmental restrictions and low traffic density. Logically, this is a world in which infrastructures have to prove they are carbon neutral. Airports, for example, must show they produce less pollution and noise, but also that they actively contribute to the overall ecological budget by using energy sources for their own operations that don't produce any CO_2, or, if this is not possible, by offsetting their emissions by setting up carbon sinks, planting trees for example. There are fewer hub & spoke systems and more airports operated point-to-point. Some of these points are connected with each other or to the hub via rail (electric trains). Depending on distances and environmental conditions, rail travel can provide a better tradeoff than air travel in relation to the environmental priorities in this scenario. Air travel itself is reconsidered by society from a comprehensive perspective, with passengers paying not only their ticket, but also offsetting the environmental cost of their trip by contributing, for example, to reforestation. This type of "CO_2 solidarity" approach, long limited to the most committed environmentalists, has become one of the fundamental aspects of society in this scenario.

Superconducting materials

Materials that transmit electrical current without energy losses. The growing importance of electrical propulsion makes this a fundamental technology. Superconducting materials already exist, but are still limited to operation at very low temperatures, which entail major technological challenges.

Hybrid propulsion

Like the propulsion system in today's hybrid cars, a hybrid propulsion system for aircraft would combine thermal cycle engines with electric motors. During certain parts of the flight, electricity can be generated by thermal engines, and at other times, directly by batteries.

Air transport in general has to demonstrate its pertinence in relation to other means of travel. Faced with these constraints, aircraft change. There are far fewer of them, because of lower demand, and they are also smaller than in the ULS scenario. Less obviously, they also reflect the breadth of possible solutions. The strong constraints imposed by society favor the emergence of more innovative concepts. The focus is on limiting emissions and saving energy, not only during operation, but also throughout the life cycle of the vehicle, expressed in the "green aircraft" concept. We therefore scrap the older aircraft with less energy-efficient jet engines, and support the massive expansion of electricity, produced by diverse sources. This change is greatly facilitated by the development of non-conventional superconducting materials, which offer virtually no internal resistance for highly efficient current transmission. Progress lies in the temperature at which materials become superconducting: raising the temperature range makes this technology far more accessible (for example, well above -170°C), thus minimizing the complexity and weight of cooling systems installed on aircraft. The Blended Wing Body (BWB), an evolution of the flying wing, is well suited to a wide range of propulsion concepts. The large internal volume offered by these aircraft (ideal for freight, or a combination of passengers and freight) also means that there is room for "buried" engines, thus generating less noise and enabling conventional internal combustion engines to once again justify their use. This type of aircraft could just as well be fitted with an electric propulsion system using energy from a small nuclear reactor in the fuselage, or from solar cells that could easily be distributed over the upper surface of the aircraft's body.

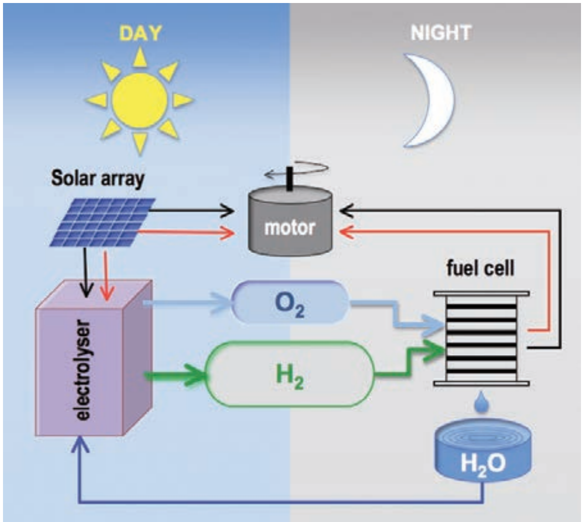
Rhombohedral wing

The regenerative fuel cell is another option. Biofuels are only considered a good solution if they offer a favorable overall energy budget, once again reflecting the system approach. It's not worth using so-called "green" energy, if we have to use so much water and diesel fuel (for tractors) and release so much gas in the atmosphere to produce the required feedstock that we are unbalancing the system in other areas. Not to mention that the land used to produce this energy source is no longer available for food. This type of intellectual approach is typical of the RPP scenario.

Propeller-based propulsion systems become more widespread. Contra-rotating layouts tend to be noisier, and are therefore mainly used on flights over unpopulated areas, for example intercontinental flights. In general, this scenario involves flights at lower speeds, as reflected in less swept wings and larger aspect ratios. Long routes are divided into more legs, mainly to limit consumption. Trials of different refueling solutions are carried out, either in-flight or via ocean platforms (also used for passenger transfers); when they generate fuel savings, these solutions will be used. However, this is not always the case, since after being refueled, the aircraft obviously have to climb back to their cruise altitude, which takes energy. That's why the concept of "tractors" is also being studied, to bring aircraft up to cruising altitude with their tanks still full. Likewise, commercial aerial tankers are being considered. In consequence, passenger aircraft will not fly as high, exposing these aircraft and their passengers to bad weather and turbulence over longer periods. This is partially offset by designing more flexible wings (damping), and by using turbulence detection devices, or controlling the effect of turbulence on the aircraft if it can't avoid it, by using MEMS (microelectromechanical system) type devices.

Regenerative fuel cell

A fuel cell that converts hydrogen and oxygen into electricity, combined with an electrolysis device that converts the water byproduct into oxygen and hydrogen, which can be reused in the fuel cell. The energy needed for electrolysis can be generated by solar panels. This type of system is capable of operating day and night, and reduces the weight needed for fuel storage (hydrogen) and electrical energy storage (batteries).



Morphing

This broad concept encompasses both “smart materials”, and real-time changes in the shape of wings and or aircraft. Smart materials react to various stimuli to change their properties, including mechanical, such as deformation, elasticity, etc. This is a major focus of research, in particular leading to the active elasticity concept. The latter case refers to devices (sometimes these same smart materials) that can change the airfoil of a wing, for instance. The underlying aim is to eliminate lift augmentation devices such as slats and flaps, which are heavy and cause excessive drag. To replace them, we generate real-time changes in the airflows over the wing, either by deforming the wing itself (via the actuation of minuscule control surfaces), or by using blowers and ducts to generate local phenomena capable of maintaining the boundary layer. This enhances aerodynamic efficiency in all phases of flight, thereby improving fuel consumption and/or controllability. These techniques are used in conjunction with smart sensors, used to monitor in real time the shape and condition of the wing, and its constituent materials, which have to be changed to adapt the wing shape to each flight phase; at the same time, these sensors keep an eye on aging, and check whether deformation has not exceeded a safe threshold. This concept is known as Structural Health Monitoring (SHM). Applying these technologies assumes that we can develop the complex computation methods capable of providing a clear idea of the strength, flexibility and aging cycles of a structure made of different materials, in which a large number of sensors have been embedded.

One very important research path is “morphing”, for instance via the “active aeroelastic” concept. This seeks to duplicate the control effects of traditional lift augmentation devices, such as slats and flaps, with their weight and drag penalties, by using real-time changes in airflow over the wing, either by deforming the wing (via the actuation of minuscule, efficiently located control surfaces), or using a fan and duct system to locally reposition air streams within the boundary layers. These mechanisms will also improve aerodynamics during all phases of the flight. These two approaches, both using powerful onboard computers, could also be combined. However, they will not exist without the development of materials with the requisite elasticity, or shape memory materials, which would naturally retain their recyclability.

If point-to-point connections were to become widespread, this would of course favor the use of Personal Air Transport (PAT) systems. Offering short or vertical takeoff and landing, plus all-electric propulsion, these systems could be easily integrated in urban environments, similar to private cars. Along the same lines, a complete family of vehicles would be offered, from a single-seater to the equivalent of a minibus.

Military flights and emergency services (medical, police, fire) would integrate the airspace as in the ULS scenario, namely by requisitioning flight paths that Air Traffic Control (ATC), in charge of managing priorities, would make available for the time needed. Private planes and trainers, instrumented to offer collaborative capability, would also retain a spot in this scenario, largely due to electric propulsion. This type of propulsion will have considerably improved its effectiveness due to the progress made on other types of vehicles, in particular cars.

Technology choices

Because the older technologies are no longer appropriate, Regulatory Push & Pull is the richest scenario in terms of key enabling technologies. It encompasses a wide array of solutions that help reduce pollution of all types, as well as the consumption of fossil fuels. In particular, it involves the widespread use of electrically-powered aircraft and, in general, innovative concepts and configurations, such as the Blended Wing Body, active airflow control and smart materials and sensors. Worth noting in terms of a comprehensive vision is the concept of “carbon neutral” that would apply to airports as well as propulsion systems. From the organizational standpoint, this scenario is dominated by the concepts of full automation and 4D contract, applied within the scope of green procedures to meet critical energy savings and traffic control criteria.

Our recommendations

The focus should be on five key technologies. Four of them are still at the nascent stage, and require sustained efforts in terms of research, development and production: electric aircraft; carbon-neutral propulsion modes; complete traffic automation; and aircraft concepts based on disruptive technologies (the only one for the moment to benefit from significant R&D). The fifth technology is the carbon-neutral airport, and all that remains to do in this area is the actual implementation. Other technologies are less crucial, except for green procedures, which are important from the standpoint of the RPP scenario. Since this scenario requires all different types of technologies, it is probably the scenario that demands the most massive support for research.

Down-to-Earth

Down-to-Earth

A world that functions with virtually no fossil fuels and generates no emissions

The third scenario presents a radical situation, reflecting a political commitment to eliminating fossil fuels. These fuels are not necessarily depleted, but society has decided to stop tapping nature, and to freeze the remaining reserves as they are. Furthermore, we no longer release polluting substances. This situation is not necessarily the catastrophic result of a period of hyperconsumption and all-out development as shown in the Unlimited Skies scenario, in which we are down to our last drop of oil. Instead, it is the result of a conscious and purposeful choice: we as a society decide that we have to stop negatively impacting our planet. Business activity is wholly subordinated to protecting our planet. Electricity (generated by nuclear, solar, wind and water power) will therefore be the predominant energy source for human activities, necessarily green.

Given this context, commercial air traffic, along with similar industries, is completely called into question, not only because it consumes energy, but also because it generates emissions and therefore contributes to the greenhouse effect. For travel within each continent, electrically-powered trains therefore become the primary mass transportation system. Intercontinental travel will call on ships with very large sails, using solar cells to provide energy for all onboard systems.

In general, however, instead of business travel, people will “meet” via videoconferences, either from their office or from home where they are teleworking. Virtual reality will meet some communications needs in a world where we can no longer travel as quickly or easily across the planet. Of course, airports no longer exist, since commercial air traffic has disappeared. The only acceptable flights are those in the public interest, or a few marginal operations that can prove they are neutral to the environment, starting with military activity.

Renewable energies take priority

Surveillance missions are also a priority

D 3

Dirty, Dull and Dangerous

The D3 concept applies to missions that are assigned to automated aircraft, because they are carried out under conditions that would not be tolerated by humans. Typical cases include observation aircraft remaining in the air for several days at a time, as well as aircraft carrying out monitoring missions in areas having experienced natural disasters.

States will still be as they are today, with defined borders and exercising sovereignty over their territory. So there are still jet or turboprop-powered military aircraft piloted by humans, for routine missions, operating alongside unmanned aircraft. These drones have changed very little from current models, except that they are fitted with regenerative fuel cells or solar cells to power small electric motors. Also considered acceptable are flights from small airfields or heliports by emergency units, for police, medical, search & rescue or fire-fighting missions. These units will make use of conventional aircraft, such as turbine-powered helicopters, for emergency medical evacuation and police missions, and water-bombers to fight forest fires. While these aircraft emit CO_2, there are so few of them that they have a negligible impact on the environment. So this “exception to the rule” becomes acceptable, especially in light of the tremendous benefits for society.

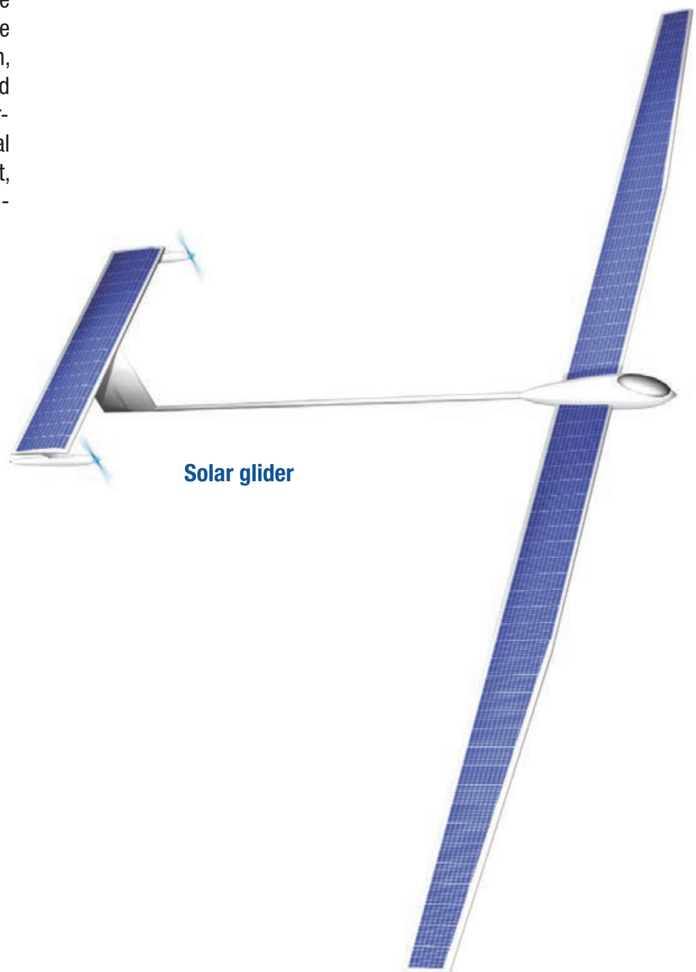
Furthermore, these aircraft could possibly use biofuels instead of oil, but only if the production of these alternative fuels does not upset the fragile ecological balance. If these fuels deplete our water resources, because of the need to water crops, then it would be better to use fossil fuels. In fact, at the rate of use according to this scenario, our fossil fuel resources could be considered virtually inexhaustible.

Automated systems will be developed to handle surveillance, observation or dangerous missions, those considered “Dirty, Dull & Dangerous” – the D3 concept. As for military drones, these systems would generally be unmanned and electrically-powered, since the principle of environmental protection also extends to human lives. Society’s tolerance for exposing people to danger has in fact become very limited. In general, although they have a specific status, soldiers, policemen, doctors and firefighters are subject to the same environmental logic prevalent throughout our society. Air force bases, for instance, will have to show that they are carbon neutral. Their emissions will be considered in the light of a holistic environmental approach, and must therefore be offset by planting trees (or other carbon sinks).

Solar power plant

Light aviation only has a role to play in this context if it is totally environmentally neutral. However, it is only natural to believe that fallout from technological progress in other sectors would help maintain aviation for sports flying and flight training purposes. For instance, electric propulsion – especially the miniaturization and performance enhancement achieved in the auto industry (not to mention the ability to recycle batteries without polluting) – could support the design of very light aircraft that do not generate any emissions and whose energy source is environmentally neutral. Gliders launched by an electric winch, or electric motor-powered gliders would be totally legitimate. All these manned or remotely-controlled aircraft (military, public interest or leisure) would operate in free flight; i.e., their operators choose their routes freely, with minimal contact with Air Traffic Control (ATC). There would be very few of these aircraft, and they would only be flying alongside highly automated aircraft, able to collaborate within a sophisticated local loop.

Electric car



Solar glider

Electric-powered motoglider

Technology choices

The focus here is on enabling technologies for electric propulsion and carbon-neutral propulsion. There will be no aviation without them, because the most urgent goal is to stop pollution and use fossil fuels as little as possible. The logical complementary factor would be infrastructures that offset their releases by using carbon sinks. Since noise is also a type of pollution, reducing noise and using green procedures are also very important. Lastly, since air traffic in the Down-to-Earth scenario is very slight, this would be the natural environment to develop “free flight”.

Our recommendations

The priority investment must be in electric aircraft, along with carbon-neutral propulsion and air bases. While the latter are nearly feasible already, this is not true for electric aircraft and carbon-neutral propulsion technologies, and a massive effort is needed in R&D and other areas. Efforts to reduce noise and apply green procedures should be continued, while free flight and a “minimal” Air Transport System are considered as less fundamental, given the expected volume of air traffic.

Fractured World

Fractured World

A juxtaposition of independent worlds, developing at very different paces

The fourth and last scenario, Fractured World (FW), offers a brand-new geopolitical vision. The world has been divided into very distinct blocs following major political and economic crises, partly caused by inequality in relation to the consequences of global warming and access to energy. Other factors include the sometimes contradictory aspirations of different peoples, depending on their history and world view. At a moment when China embarked on a policy of accelerated production, along with a consumer appetite that was all the stronger because so long repressed, countries in Western Europe, united by common interests and having long trod the same path, were beginning to realize that they had to stop this same headlong pursuit. Each bloc therefore drew back into its shell, and chose its own solutions according to what it considered its basic values.

These groups of nations, relatively homogenous in geographical terms, are each roughly on a continental scale. The atmosphere is largely paranoid, and while a few resources seem to remain, notably fossil fuels, they won't last much longer, and above all there won't be enough for everybody – even those who live in a favored zone.

So the different blocs keep a wary eye on each other, ready to leverage the slightest competitive edge. The resulting tensions lead to an increase in military air traffic (among other reflections of sovereignty) within and at the edges of the different blocs. It is of primary importance for the states comprising these blocs to ensure their security in relation to other blocs, as well as in relation to their immediate neighbors. Trade between these now independent zones is now only marginal, which effectively eliminates long-haul air transport. Instead, various long-range communications solutions have been developed, and citizens no longer fly to the other side of the world on vacation – except virtually. A regional aviation industry still exists within the blocs in the best of cases, because not all of these groupings have developed equally.

Some, comprising very rich countries with natural resources and continuing political influence, still have the means to allow their economies to move forward. So they are operating according to the first scenario, Unlimited Skies (ULS). In this type of zone, air traffic has been allowed to expand without hindering it with restrictive environmental regulations. It is also worth noting that this case involves a vast land area, not overcrowded, with non-negligible fossil fuel resources.

Supersonic business jet

Open-rotor engine aircraft
without a human pilot aboard

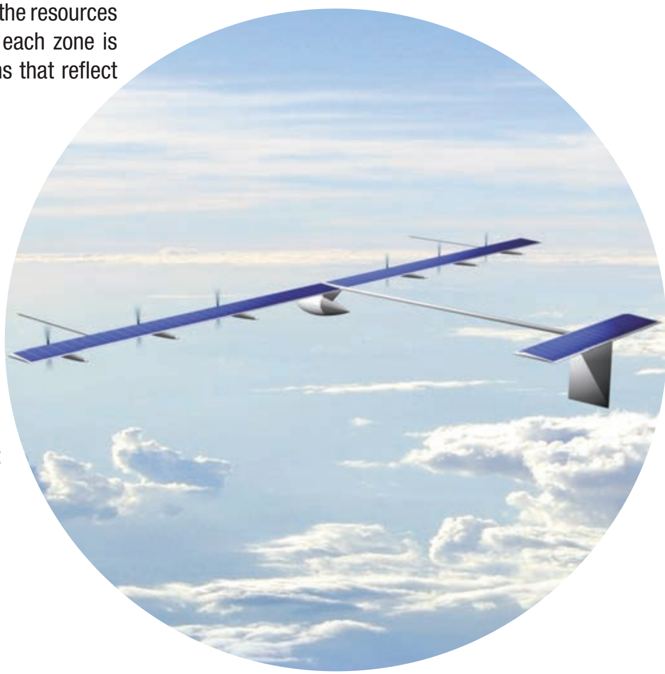
The priority is therefore still on economic and industrial growth, without the sustained social and political will to limit growth. This situation could continue as long as citizens are not subjected to unacceptable living conditions, forcing political authorities to pass laws. Among these conditions are the increasingly expensive access to energy, and the pollution inherent in expanding air traffic. The only real constraint is to avoid saturation. That's why efforts focus on making traffic flows smoother by control systems making massive use of automation (full automation and 4D contract). Long-haul jets have disappeared, replaced at the summit of the mass transport pyramid by unmanned medium-haul aircraft. As a result, international airports have also disappeared. The infrastructure network is still organized in dual fashion, combining hub & spoke operations (but without their current international scope) and point-to-point routes. Also characteristic of this scenario are a very wide range of business aircraft (all the way to supersonic jets), and Personal Air Transport vehicles, which tend to replace private cars.

This comparatively rich world, or worlds, exists alongside poorer zones, which have neither the same resources, nor the same influence. Their inhabitants are more conscious of the limits of their lifestyles, and of its fragility in relation to the upcoming depletion of fossil fuels. Without sounding the death knell of its industry, these blocs regulate their activities, with a priority objective being to reduce environmental impact. This has become a major political concern, supported by all of society. So these blocs naturally adopt the Regulatory Push & Pull (RPP) scenario, which no longer subordinates its political choices to the interests of the market, and capitalizes on automated traffic management to meet the objectives of environmental protection and drastically limit pollution's impact on people.

The full automation and 4D contract concepts are used to meet this specific goal, while the spotlight is resolutely on green technologies that will minimize consumption and emissions: electric propulsion, high or even infinite aspect ratio wings, lightweight materials, innovative configurations such as Blended Wing Bodies and PAT. The most innovative technologies will be implemented in these blocs, quite simply because the required tradeoff is the most difficult to achieve: produce and consume more, but while integrating the consequences. A comprehensive approach will be used. This type of zone is smaller than the other zones, which will foster the use of smaller aircraft sized for regional transport, with limited speeds and altitudes.

There are other zones as well, which have decided to change their approach, either by necessity, or by choice. Instead of consumption that draws on natural resources, and human activities that pollute the environment, the inhabitants of these zones have decided to freeze natural energy resources as they are, and to use only renewable energy sources. A bloc of this type would operate according to the Down-to-Earth (DTE) scenario. Commercial air traffic no longer exists. Aviation is therefore limited to military and public interest missions, which means it is so widely scattered that it can operate in free flight mode without any problem.

The fact that these zones have withdrawn into themselves does not mean that they do not influence each other. In particular, it is hard to imagine that a country operating according to DTE logic would easily tolerate the headlong growth typical of ULS. While the political organization and strategic decisions have resulted in a fragmentation into blocs of countries, the borderless air and ocean currents would tend to convey the emissions generated by certain blocs towards the natural sanctuaries set up by others. But does this mean that such differences in lifestyles are destined to be reduced in the case of a major crisis that would terminate the Fractured World scenario? Not necessarily, because, if entire areas of the world operated according to RPP, or even better DTE, that would enable, through a balancing effect, other blocs to remain in ULS mode for a longer time – exactly as though a global offset was occurring. However, it is also possible that things would not evolve like this. Rather, under international pressure, countries worldwide would collectively decide to adopt more or less the same lifestyle, but modulated according to the resources at their disposal. At this point, fragmentation would mean that each zone is drawing back into itself in order to organize the living conditions that reflect the effort that each society is ready to make.



Solar-powered aircraft

Technology choices

These choices vary according to the situation in each separate bloc, and the approach each has chosen.

Our recommendations

The decisions to be made depend on the scenario, and overlap with those given at the end of the three previous scenarios.

Research

paths for a viable air transport system in 2050

The four scenarios described in the preceding pages are designed to support further analysis. They are rough sketches that describe highly contrasted situations, clearly bringing out their organizational foundations and their research requirements. Because the actual situation and trends are always more subtle and complex than this type of exercise can show, it is doubtful that the air transport industry in 2050 will correspond totally to these scenarios.

This study does not pretend to be a crystal ball. Its aim is instead to foster the development of a road map. The infinite variables at play, the fine balances possible, and the way in which history will shape the next 40 years mean that at least certain characteristics of the world of 2050 will be brand new. However, we will still find a preponderant share of the characteristics described in these four scenarios, and in consequence, the associated technologies, concepts and systems. These solutions are basically designed to allow people to use air transport to maintain their mobility, without at the same time sawing off the branch they're sitting on. In turn, this implies betting on certain areas of research, including new aircraft concepts and technologies, automation and traffic management, airport infrastructures and of course critical design and testing tools. Any decisions made in these areas have to address a two-pronged concern: to protect the environment and reduce the consumption of energy. This must be considered from a holistic "system" approach, the only one that takes into account the actual impact of applying any type of solution, from production to operation to recycling, and spanning all interactions with the environment.

Aircraft

Rethinking the architecture and all-out development of cross-disciplinary technological building blocks

Two research paths in aircraft design must be pursued concurrently: the development of new technologies that could be integrated on all types of aircraft, and rethinking aircraft architectures. The conventional configuration of transport aircraft is dictated by the principle of separating the three main functions of payload (fuselage), lift (wing) and propulsion (engines), enabling each of these subsystems to be treated virtually individually in order to maximize benefits. Since this configuration has probably reached nearly optimum performance, it offers only very limited room for progress. It is therefore necessary to rethink the problem as a whole, enhancing efficiency by integrating all functions. A change in approach of this type naturally calls into question the current production organization, in which each sector (airframers, engine-makers, equipment suppliers) enjoys relative autonomy. Which means that the industrial landscape and its balances of power will have considerably changed by 2050.

The significant advances in a known concept, the Blended Wing Body, or BWB, perfectly illustrate the need to move forward in step – and across the board – in terms of new architectures and innovative technologies. Of course, this configuration enables an advantageous increase in carrying capacity at lower energy cost (assuming that a need for large capacity aircraft still exists). The BWB's aerodynamic advantages, coupled with an intrinsically low structural weight, holds out promise of a significant reduction in fuel consumption. The large interior volume could be used for a better mix of passengers and freight, as well as to “bury” engines in the airframe. Although this type of propulsion layout could make maintenance a bit harder, it would also decrease drag and noise (a decisive factor in people's awareness of the disturbances of air traffic). Decreasing the noise footprint also depends on the integration of generally passive noise-absorbent materials, greatly facilitated on a BWB. However, efforts are needed to ensure that these materials do not penalize energy efficiency, are stable over time, and do not make maintenance operations prohibitively complex. Active noise attenuation devices also have excellent potential to reduce cabin noise, particularly in narrow frequency bands. Here too, the focus is on mastering robustness and aging.

Electric-powered blended wing body (BWB) aircraft

Hydrogen-fueled aircraft

By pushing the BWB concept a bit further, it is also possible to rethink propulsion, in successive stages. A first step would be decoupling the power generation and propulsive functions, possibly leading to the development of a distributed propulsion system that would provide additional aerodynamic benefits. Individual engine control would contribute to flight control, instead of or in conjunction with conventional control surfaces, along with jet deflection or active airflow control devices. Another way of optimizing the energy budget during different flight phases would be controlling surface geometry, achieving small deformations via MEMS (microelectromechanical mechanisms), or using elastic, aging-tolerant materials. These solutions also bring potential benefits in terms of decreasing acoustic sources. However, this would require more extensive research on smart materials, the aging of materials in general, sensors and information processing (large, high-rate data streams), as well as distributed actuators for flight control surfaces. At the same time, we will have to ensure the dependability of these systems. All of these efforts will have to achieve a degree of maturity, based on the study of concepts drawing on these technologies, that achieves an optimum tradeoff between the total weight of these devices, their aerodynamic improvements and their complexity.

We could go even further in terms of propulsion, in fact, all the way to new energy sources. Our ongoing aim, of carbon neutrality, is feasible, and there are several ways of meeting this goal: either by calling on an intrinsically carbon-neutral energy, such as solar or nuclear power, or by using an intermediate source that does not release CO_2 in operation, namely hydrogen. The development of production technologies for this gas, capable of limiting releases – and also easily capturable – would achieve an ecological balance. We must therefore develop production solutions, and in particular pursue our efforts on all technologies enabling the use of hydrogen-based fuel on aircraft: chilldown, maintenance at low temperatures, lightweight, insulating structural tanks. Last but not least, a carbon-neutral solution should not also involve a significant increase in the release of other pollutants, such as sulfur compounds.

An electrical generator driven by a hydrogen-powered turbine could supply power for a large number of high-efficiency electric motors. However, superconductor connections would be needed to ensure the overall efficiency of the system. By reducing losses, these superconductors would in effect increase the power-to-weight ratio of the engines and the capabilities of the associated electronic power controllers. Research efforts should also therefore focus on these materials. The use of electric motors should obviously be considered in terms of a tradeoff between energy and the environment, implying that the initial application would be on small aircraft. However, advances in this type of propulsion will only be advantageous if the total energy budget over the entire life cycle (including the aircraft seen as a whole) meets the objectives stipulated in each scenario. That would include energy storage devices combining high efficiency and recyclability.

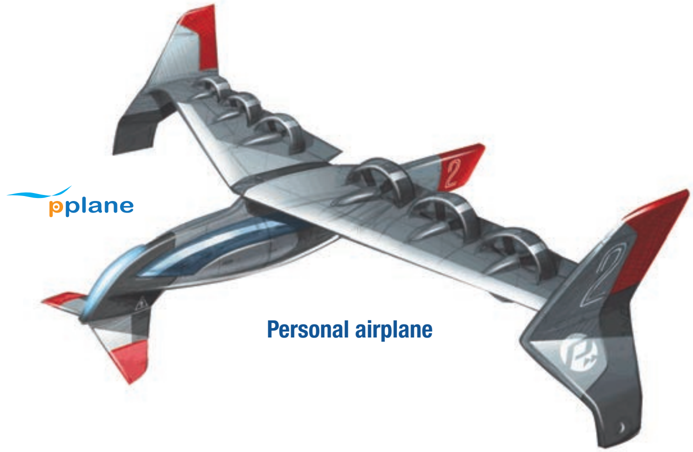
The Blended Wing Body is not the only configuration we should be considering. We could also consider trisurface airfoils, aircraft using braced wings, or infinite aspect ratio wings. For example, in an architecture that separates functions, a rhombohedral wing could offer non-negligible aerodynamic gains by eliminating marginal vortices. However, the resulting internal structure would be complex. At the same time, we would have to focus on developing certain innovative technologies to better manage loads, in terms of controlling the elasticity of structural parts such as the wing. This would reduce the necessary design margins, which in turn means lower empty weight.

From this standpoint, it's worth taking a close look at composite materials. Their resistance to local degradation is a major concern, in relation to flight safety and therefore the resulting design margins. Miniature sensors must be integrated to better monitor these structures. It would also be a good idea to conduct more basic research on wood fiber-based composites.

Other new-generation propulsion concepts are based on high-speed propellers, possibly in a contra-rotating layout. In this case as well, their energy benefits must be seen in light of their environmental and societal benefits. Progress in these areas is also possible on essential subsystems, such as the landing gear. Only a multidisciplinary analysis could confirm the advantages of these technologies, by properly estimating the tradeoffs that they would necessarily have with aircraft performance in terms of fuel consumption and polluting emissions.

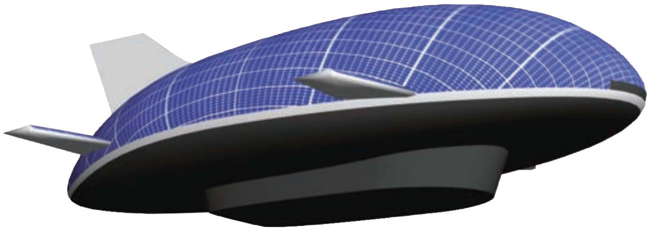
Innovative solutions will also be generated by exploring paths that are known, but of still limited interest. Achieving several key technological breakthroughs would enhance their operability, even if applications remain limited to a niche market. Airships, for instance, could hover over an area of interest – like satellites, but at a much lower altitude – for use as a communications relay, or to conduct surveillance from the troposphere or stratosphere.

Nor is it out of the question for disruptive technologies to come along at the right moment, providing the opportunity to reconsider the problem of flight from a brand-new angle. For example, we have to develop alternative lift solutions that would give definitive impetus to the Personal Air Transport (PAT) concept. If not, it is also perfectly possible that this type of individual vehicle would continue to use a conventional aerodynamic design, provided that its propulsion system limits the noise generated within cities, and that it limits energy consumption; i.e., is electric. Furthermore, based on previous technology trends, the PAT could well be the first vehicle to benefit from advances in this type of propulsion well before the large airplanes that are the primary target, but for which the feasibility of all-electric propulsion will be very hard to prove.



Personal airplane

Personal helicopter



Solar airship for tropospheric suveillance missions

Another important aspect, for any type of flight, is to protect our aircraft, and not necessarily by direct military action. Depending on the threats involved (such as terrorism), transportation safety must be able to count on self-protection devices developed for military applications.

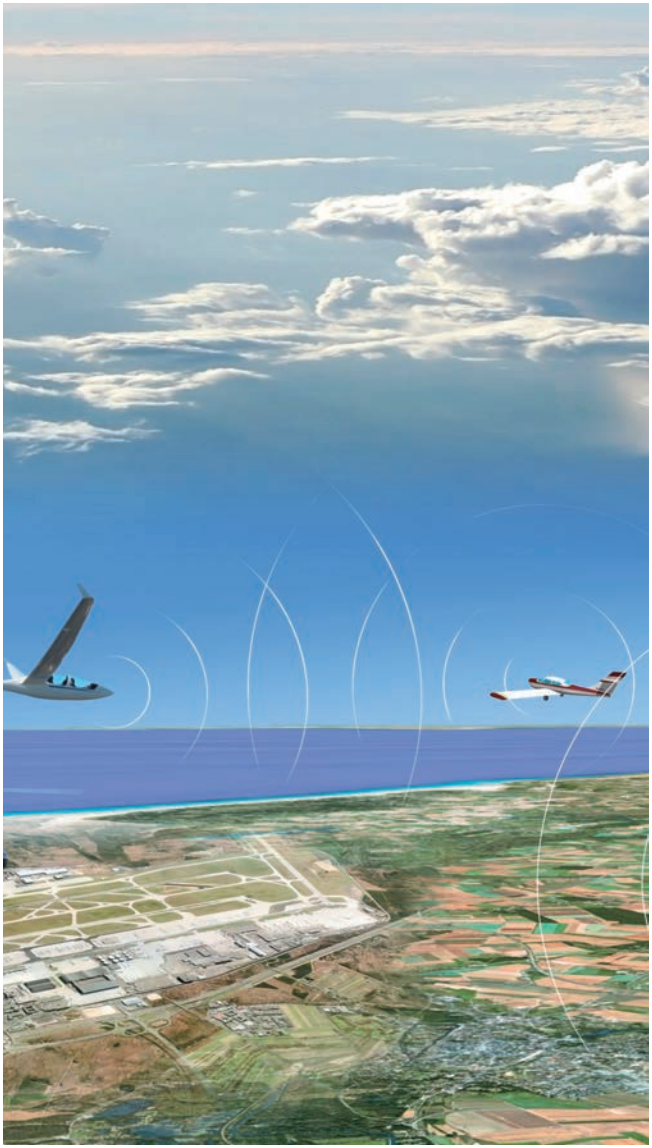
This multitude of technologies demands a multidisciplinary, multicriteria approach. The necessary new tradeoffs, combined with the asymptotic effects seen today on some of these configurations, mean that all the reappearing coupled phenomena have to be integrated and modeled. Only by thoroughly understanding them can we draw the utmost from these concepts.

4D contract and automation

Powerful algorithms and resources to enhance system reliability

We still have a long way to go in developing green flight paths and the 4D contract. This is especially true in a world that is increasingly sensitive to the environment, where air traffic saturation is becoming a real problem and where energy is expensive. Under these conditions, there is a clear necessity for aircraft to follow optimized flight paths, since they generate significant energy savings and limit pollution, as well as maintaining safety at an acceptable level – except of course if commercial air transport collapses. More precise flight paths would also enable reducing separation distances between aircraft, to increase traffic flows. This is perfectly feasible with the technology at our disposal today. Simulation systems enabling us to evaluate flight path plans (4D contracts) are already within our grasp. However we still need a major effort to validate these calculations, so that the results convince airlines and other operators that it is worth it. They would have to adapt to these procedures, in terms of fleet management and flight schedules. Several obstacles remain, including the classic one in this sector of having to produce equipment to handle the new procedures. Furthermore, we would have to prove the robustness of the system itself (tolerance of software, hardware or system failures), and show that it meets specific performance objectives, especially the Key Performance Areas defined by the International Civil Aviation Organization (ICAO): safety, punctuality & predictability, capacity & delays, flight efficiency, cost-effectiveness and environmental impact. From the technical standpoint, the most challenging research needed is the development of certifiable algorithms capable of carrying out high-speed calculations for 4D contracts.

From the standpoint of the aircraft itself, meeting constraints of this type will depend on the refined integration of aircraft performance, weather conditions and surrounding traffic. Because of its size and the number of parameters involved, this data is especially complex. We will have to automate calculations for a flight plan, adjusted to conditions at a given moment, and optimized according to the general or possibly specific criteria of each operator. Each aircraft will have to be capable of re-evaluating its flight path “on the fly”, to deal with unexpected (and unforeseeable at the scales in question) changes in weather conditions and the flight paths of other aircraft. A human pilot would have great difficulty in reacting quickly and accurately enough to evaluate conditions and track the flight path at any given moment. Aircraft must therefore be automated, transferring to this system some of the tasks previously handled by people.



That means actually flying the aircraft, of course, but also communications with the traffic management system, navigation and handling unplanned events. One resulting advantage is an increase in safety because of the elimination of accidents due to pilot error. Likewise, traffic will be far more predictable, and organizational changes could generate savings.

It will also be simpler to design aircraft that don't have cockpits. On the aircraft itself, automation will depend on the use of a Flight Management System, or FMS, capable of taking charge of the entire mission: from push back to parking on arrival, along with taxiing, takeoff, climb, cruise, descent and landing. Furthermore, various digital communications links will have to be installed to connect the traffic management system (the ground segment in particular, also automated) and the aircraft. In relation to the situation today, the implementation of these two elements will require certain major advances, particularly the development and validation of software controlling all aspects of a flight. This software will have to be capable of automatically managing emergency situations, communicating with the traffic management system, and even interacting with surrounding aircraft. An additional imperative is the validation of this software, which will obviously have to offer superior reliability.

Datalinks are the other essential pillar of automation. They will have to offer very high performance, not only between the various aircraft sharing a given part of the airspace, but also between aircraft and ground segment. In addition, we have to provide initial and in-service staff training, since people are still part of the equation. The presence of a technical flight crew on the aircraft will probably still be necessary, in particular to check system integrity, carry out certain non-critical repairs, etc.

In addition to these technical efforts, the application of automation also depends on resolving certain technical and societal issues. Among the former are the transition between the current system and an automated system, a critical period during which not all aircraft will be equipped to the ultimate standard. This is undoubtedly the most crucial aspect of the changeover.

We will also have to cope with a considerable cultural upheaval: passengers will have to accept traveling on a plane without a human pilot aboard. But will this still be an obstacle once the system has demonstrated its reliability? We will have to deploy the resources needed to achieve this, including proving the system's capability under all possible situations. And we will also have to determine all related legal responsibilities.

Airport infrastructures

Optimized logistics, taking into account transition phases

Our airports must also be emissions-neutral, especially for CO_2. Achieving this goal assumes that sustainable development principles will be integrated right from the design stage, in terms of cost, energy, pollution and of course recycling. A significant part of the challenge overlaps the situation in urban and industrial architecture, especially construction without using "dirty" techniques or materials. But this approach also encompasses the idea of airports within a multimodal transport network including roads and railways.

At the same time, we have to resolve the problem of operating and supplying these huge infrastructures, including heating, ventilation and air-conditioning (insulation), electricity, air, water and goods. It is possible to consider local energy production for the entire platform, taking advantage of the vast surface area available, and its location away from city centers. Electricity could be produced by wind or geothermal power, or transmitted from distant power stations. The distribution of passenger gates according to airlines and destinations must also be optimized at large airports. Unlike the situation today, airplanes should no longer have to taxi for a dozen kilometers to get to the runway. We could also design more user-friendly solutions for the aircraft, such as boarding via integral passenger modules, or, in particular with the BWB type plane, a more efficient distribution of payload between passengers and freight.

All of this will require modifying the terminals as well. Automated tractors could be used to bring the aircraft up to the runway threshold, to reduce the time that engines operate at idle, which generates a large amount of pollution, as well as increasing the amount of fuel planes have to carry. For the same reason, we should study takeoff assistance systems, such as catapults or downhill takeoffs. The ultimate aim is to decrease dead weight and augment the payload (and/or lighten the airplane), as well as making more rational use of energy. Current research on alternatives to fossil fuels show significant restrictions on having fuels in a form that can be carried on airplanes. Storage, as well as thermal, mechanical and electrical processing, is much simpler on the ground, where the size and weight of the equipment needed is far less of a problem.

None of these possibilities represents a technological revolution: the required research will concern the design of the overall system, and enhancing its logistic efficiency. The use of advanced simulation methods will be decisive.

Airport infrastructures as part of a co-modal transport system

The investments needed to start production and deployment are in fact way too high to be undertaken without a convincing demonstration of the actual advantages to be gained.

Another obstacle is fleet standardization. For example, any taxiing or takeoff assistance system would require a modification to aircraft (as well as to procedures and pilot training). Outfitting an entire fleet in one fell swoop would not be realistic. So we have to support the concurrent operation of the new and old models, allowing time to gradually replace the latter.

There is also the question of which system will emerge triumphant: point-to-point or hub & spoke? In Europe, the future seems to point to a mixed system, relatively close to the latter option. Because of the medium distances between major cities, trains are often faster door-to-door, and cost less. Another factor is that airports cannot be located closer to cities because of the disturbances they generate (environment, safety). The issue of energy – and therefore the cost of the trip for the user – also argues in favor of multimodal transport. Research into the optimum solutions will primarily call on models and simulations of “systems of systems” in this area. The optimum organization in fact depends very little on the actual technologies of the transport modes in question. Over and above the usual economic constraints, managed by the players involved (local communities for airports, operators for fleets and routes), the new global constraints (energy, environment) may require a more conceptual approach on the continental level, rather than the relatively self-organizing approach used until now.

Design and testing tools

A multidisciplinary, multicriteria approach

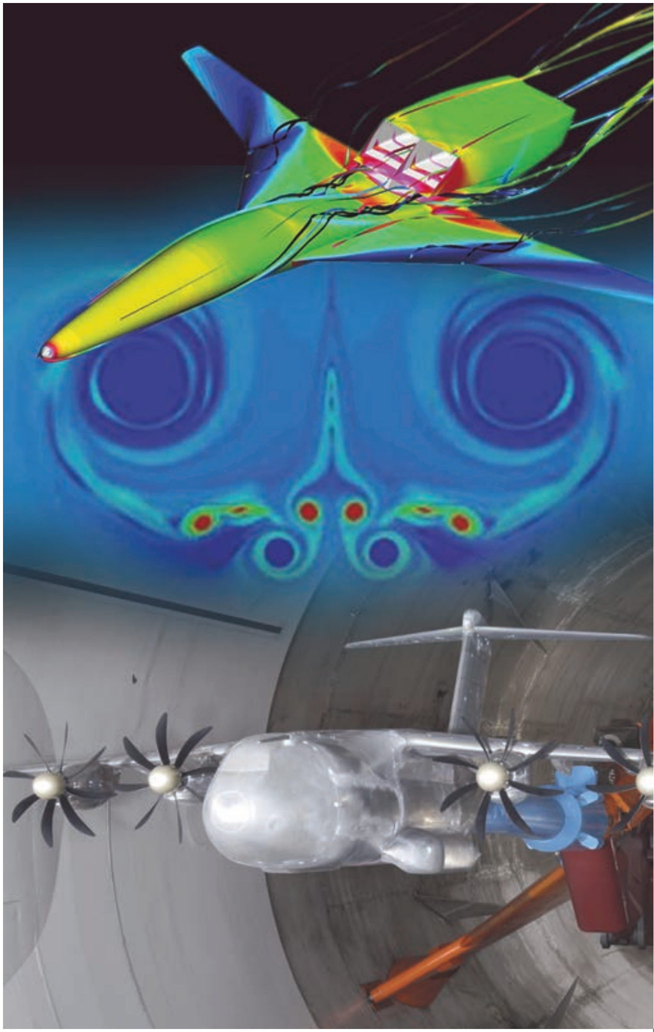
Design tools offer immense scope for development, because of ongoing improvements in technologies, which are increasingly sophisticated and interrelated, meaning they have to be considered from a “holistic” perspective. In addition, we have to integrate more and more operational, regulatory and societal constraints, in configurations whose components interact more strongly than ever.

No matter which scientific discipline is involved – aerodynamics, structural mechanics, aero-acoustics, etc. – the expected gains are now subordinated to the integration of complex phenomena, demanding extremely refined modeling and powerful computation. Modeling presumes an understanding of the phenomena involved, which in turn demands extensive basic research efforts, combining theory and experimentation. Being able to integrate these phenomena in digital modeling approaches – critical if they are to be widely used in the analysis of complex systems – assumes the development of powerful distributed and parallel processing system.

But we also have to develop analysis and investigation methods to help experts understand the quintessence of these new models. In addition to this targeted vision of design, there is also the notion of interaction between disciplines because optimum solutions depend on phenomena which are increasingly coupled and hard to observe. This implies systematically embracing all the disciplines involved, at a suitably high level of complexity to fully represent the richness of actual situations, to develop the models which alone are capable of meeting the required performance objectives.

However, in our current organizations, the competencies and modeling processes available in each discipline or subsystem are controlled by individual departments which have trouble collaborating closely with the others. This is simply because the cultures are very different, and people in each discipline are unfamiliar with the constraints and complexity faced by their counterparts. We have to break with this way of doing things, and offer methods and tools that enable us to successfully apply this multidisciplinary design and optimization approach.

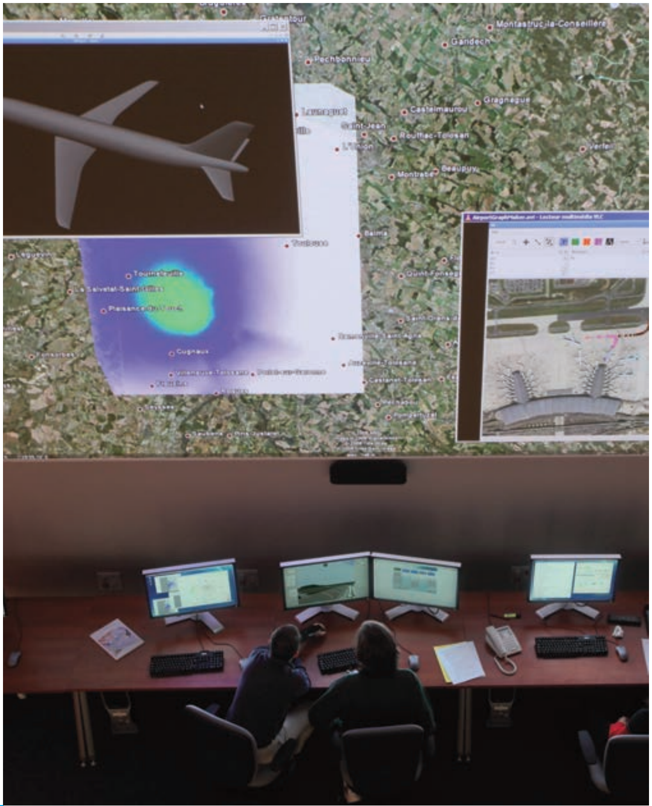
There is still vast room for progress. From the theoretical standpoint, for instance, we must define strategies for robust and reliable design, in order to



manage the uncertainties of models and their input data. Another objective is the ability to calculate stable optimized solutions as a whole, largely unaffected by the natural range of conditions of use, whether operational or environmental. These processes will continue to demand heavy computing power, as well as storage and post-processing analysis to support decision-making. They will call even more widely on distributed processing for significant data throughput, as well as virtual reality applications, the development of which thus becomes a priority.

We will only be able to use a number of technological building blocks once we have proven their validity. Whether they concern new aircraft, a reorganized air traffic control system or new flight procedures, these blocks will have to be validated within the overall air transport system. Unfortunately, given the complexity of this system and its governing regulations, it is generally impossible to carry out a full-scale exercise of this type under real conditions, except for technologies that can be tested in flight (development of an open rotor, avionics, etc.). Simulation is therefore the only means of measuring the benefits of these new concepts. But the only off-the-shelf test tools of this type are generally each dedicated to a single performance criterion, such as noise around an airport, overall noise footprint of a continent, local and global chemical emissions, the cost of air traffic, etc. They are based on measured data, statistics, or semi-empirical laws, which means they call on our historical knowledge of aeronautics. This is in fact a legacy of the way this sector has always developed over time, in small steps, or case by case, largely based on reactions to specific accidents.

IESTA, the French air transport system evaluation infrastructure



However, the current trend is to consolidate the existing evaluation tools, grouping them within a single infrastructure. This is the case, for instance, of the French project IESTA ("air transport system evaluation infrastructure"), the European project SPADE (Supporting Platform for Airport Decision-making and Efficiency analysis) and the American project AEDT (Aviation Environmental Design Tool). These are automated simulation tools operating in time-accelerated or time-constrained mode. On the other hand, when we study the real operation of the system, especially to know how it is impacted by human factors, we use real-time simulators that call on people whose role is to reproduce the behavior of the actual system actors (controllers, pilots). Today, there is a dichotomy between these two types of simulation, which are complementary, although generally not linked. If the air transport sector evolves towards a more automated, and therefore more deterministic system, we could focus on simpler behavioral models, while still remaining representative, which would give us a broader and more flexible scope for modeling. Furthermore, networked gaming applications offer simulations of virtual societies that model a large number of agents with personalized behaviors based on artificial intelligence. Eventually we could use universal simulations of a complete, complex system, as for air traffic seen as a whole.

With the advent of revolutionary technologies, evaluation tools must be capable of integrating innovations which are still largely unknown. We must therefore totally revamp the way in which we design these devices, using models that are primarily based on laws of physics, rather than capitalizing on historical data and statistics. This presumes not only that we are capable of modeling all these innovations, but that we can do so at several levels of complexity, depending where we are situated in the process.

In general, we can consider three levels: the airplane itself, traffic around the airport, and traffic on a continental or global basis. This was the approach chosen for the platform to evaluate new green concepts and vehicles within the scope of the European program Clean Sky. It is an important step, but not enough by itself.

One of the critical areas where investment will prove decisive is safety. This is obviously the first performance criteria to be considered in aviation. Paradoxically, however, it is the criterion that we are least able to evaluate at the air transport system level. Today, we do this “after the fact”, based on incident and Airprox. reports. Some of this research is designed to provide a preliminary evaluation of safety based on traffic complexity indices. Unfortunately, we do not yet have a method capable of integrating not only traffic characteristics but also all the other parameters that could impact safety, namely weather conditions and above all human factors – the most difficult.

As recent events have shown, air transport is highly vulnerable to malicious acts. This is true to such a degree that repeated acts of this nature could even lead to the disappearance of the sector. It is therefore essential that a massive effort be made to model the operation of the system, prioritize the possible failure modes and define an approach that would reduce them over the long term. Large-scale simulation systems will play a role in this area, to test various crisis situations, starting with terrorist attacks, or even predict behaviors and situations that we hadn’t considered. ■

Priorities as we see them

The number of areas in which research efforts are needed in the coming years is large indeed. All the underlying technological building blocks are important, but there are five in particular where an effort is fundamental, quite simply because their current state of development is still rather weak. These five areas are: the **electric aircraft**, **innovative aircraft configurations**, **carbon-neutral propulsion**, **carbon-neutral airports**, and the **complete automation of air traffic**.

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