THE EREA VISION ON HIGH PRIORITY RESEARCH AXES TOWARDS AIR TRANSPORT SYSTEM 2050

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Abstract

Europe is writing the future of its air transport in the new Strategic Research and Innovation Agenda. In this open context of building the future of aviation, the research centres have a key role in providing their vision independently of any economic interest. Therefore, the association of the European Research Establishments in Aeronautics (EREA) is committed to provide to the European commission and to the aeronautical community in general its vision on the 2050 air transport system and its recommendations on high priority research axes to be funded in order to pave the way towards 2050. The study briefly presented here has investigated five interdependent technological domains identified as priority and common ones to any scenarios of the future: aircraft configurations, on-board sub-systems, propulsion systems, airport and the automation issue of the air transport system.

1. General Introduction

Europe is preparing aviation 2050. Indeed, the European Commission is preparing Horizon 2020 through the Common Strategic Framework Programme for research and innovation that will be the next main instrument for funding research in Europe. The part dedicated to the transport domain and more specifically the aeronautics chapter is under preparation through the Strategic Transport Technology Plan, the Flightpath 2050 report of the High Level Group on Aviation Research [1] and finally the Strategic Research and Innovation Agenda to be prepared by the Advisory Council for Aviation research and innovation in Europe (ACARE). In this open context of building the future of aviation, the research centres have a key role in providing their vision independently of any economic interest. Therefore, the association of the European Research Establishments in Aeronautics (EREA) has decided to provide to the European commission and to the aeronautical community in general its vision on the 2050 Air Transport System (ATS) and consequently its recommendations on high priority research axes to be funded in order to pave the way towards 2050.

Following a first study providing a high level vision on the ATS 2050 [2], EREA has conducted a second phase of this study on the ATS 2050 in order to go more deeply in the promising break-through technologies roadmap [3]. Therefore, the study has investigated five interdependent technological domains identified in the first phase as priority and common ones to any scenarios: revolutionary aircraft configurations, on board subsystems, propulsion systems, airport and the automation issue of the ATS.

2. Challenges and objectives to reach 2050

In accordance with challenges identified in the Europe's Vision for Aviation [1], the EREA study investigated revolutionary ideas within the five major technological domains of the ATS with regard to the following non ordered list of objectives:

- Environmental impact: noise, chemical emissions, recycling
- Passenger aspects: mobility choice, affordability, comfort
- Safety: accident rate reduction
- Industrial competitiveness (design and production methodologies)
- Performance: Increase of transportation capacity/performance

The five domains, that are *Aircraft configurations*, *Propulsion*, *On board subsystems, Towards full automation?* and *Airport* are successively presented in the following chapters.

3. Aircraft configurations

3.1. Shaping the future

The configuration of civil aircraft has evolved little since the 1920s. Almost without exception, passengers have been transported in a tubular fuselage, with the empennage at the rear and the engines mounted either under the wings, or at the rear. Although major advances in aerodynamics and flight control systems have contributed greatly to improving the performance of the classic configuration, the advent of new design materials and design processes, along with a far better understanding of the aerodynamic and structural interactions that occur in different phases of flight, are driving some radical ideas for the future.

It is now therefore possible to consider some of the enabling technologies needed for revolutionary configurations and identify potential technical solutions and their integration within the overall air transportation system. Since these perspectives and their related technologies are closely linked, a system integration-oriented approach must be taken. Whether they are single subsystem technologies or completely new aircraft configurations, studies must always consider integration with different levels of the air transport system.

The two following paragraphs highlight different single aircraft technologies and some promising aircraft configurations, which might contribute to the Flightpath 2050 challenges.

3.2. Key single technologies for innovative configurations

3.2.1 Drag reduction

- **Increased wingspan**: wingspan is the main parameter controlling vortex-induced drag. Slender, high-span wings (i.e. high aspect ratio) generate less vortex-induced drag, but may result in a heavier wing structure. Early jet transports favoured wing aspect ratios of around 8. This requires stronger structures to carry the resulting bending and torsional moments without increasing the structural mass. Tuning spanwise lift distribution with movable trailing-edge devices is promising. There could be a potential 10% fuel burn improvement if airport terminal layouts allowed for increased wingspan in future aircraft configurations, but this should be balanced against increased aircraft mass and operational flexibility.

- **Wingtip Devices**: the right choice of wingtip device and its integration into the aircraft is a key research area. The aim is to maximise efficiency in cruise, where drag reduction is crucial. Winglets are the most popular wingtip device, and are already in used on some aircraft. Other designs include the wing grid, wingtip sails and spiroid, as well as the wingtip turbine, which can recover some of the energy losses caused by vortex-dependent drag and use it to drive a generator. Wingtip devices could bring cruise fuel savings of up to 10%.

- **Wetted Surface Area**: vertical tailplanes are sized for ensuring lateral stability, crosswind landings and complying with one engine-inoperative safety requirements. For modern fly-by-wire aircraft lateral stability can be relaxed and sizing becomes dependent on the one-engine-out scenario. Double-hinged rudders can reduce tailplane area by as much as 15%, which might produce a 0.5% fuel burn reduction. This could be increased by passive or active flow control devices to further increase rudder efficiency.

- **Turbulent Boundary Layer Drag**: current transport aircraft achieve almost fully turbulent boundary layer flow over all wetted surfaces. Although the physics of fully turbulent flow is well understood, there are still opportunities to reduce turbulent boundary layer drag. V-grooved riblets have shown substantial reductions in skin friction. Wind-tunnel and flight testing have indicated potential aircraft fuel burn savings of up to 2%. In-service trials revealed premature wear of riblet films, however - an area of continued research. Controlling turbulent boundary layers with smart Micro-Electro-Mechanical-Devices (MEMs) on all surfaces holds real potential. A more detailed understanding of unsteady turbulent substructures and how to modify these actively to achieve drag reduction needs to be developed. Because experiments are very difficult to perform, pure aerodynamics research needs to be complemented by continued effort on technologies such as high-performance computing (HPC) for virtual simulations of new configurations.

- **Laminar flow** promises a potential 5% - 10% fuel burn reduction, with the benefits increasing the longer the aircraft is in cruise. While the aerodynamic principles are well understood, the production and operation of the extremely smooth surfaces presents challenges. Forward-swept wings are beneficial for achieving natural laminar flow at relatively high Mach numbers and can also help to prevent fuselage boundary layers from interfering with the wing leading edge flow. Natural laminar flow can be applied to components with slightly swept leading edges, such as engine nacelles. Hybrid laminar flow can be achieved by embedding perforated suction panels into the leading edges of highly-swept wings and tail surfaces for aircraft flying faster than Mach 0.7. New structural technologies like morphing leading edges may enable the generation of lift at low speeds for take-off and landing with a laminar flow wing. Other design options would reduce parasitic drag due to external roughness and wakes due to windscreen design, windscreen wipers, rain rims over doors, inlet and exhaust ducts, and door handles etc.

3.2.2 Mass reduction

- **Integrated structural design**: composite materials and manufacturing technologies allow for the design of more integrated structures with fewer fasteners, reducing weight. Other advantages compared to metals include fatigue damage resistance, corrosion resistance and thermal insulation. These materials' drawbacks are, in general, their sensitivity to impact, limited damage tolerance properties and low electrical conductance. Composites already represent up to 50% of the structural weight for the most modern commercial aircraft, such as the Boeing 787 and Airbus A350.

- **Aeroelastic tailoring**: aircraft wings are designed such that their shape yields optimum lift and load distribution, but these values vary as the wing is deformed during flight. Aeroelastic tailoring can generate wing designs that deflect under loading in such a way as to moderate the internal load increase. Composites are particularly useful for this type of design because, by orienting fibres in specific directions, the stiffness characteristics of the structure can be designed to give precisely the deformation response to the experienced loading to achieve the optimum wing shape.

- **Self-healing materials**: a structurally-incorporated ability to repair damage caused by mechanical use over time. Current research on composite materials will expand the scientific understanding of self-healing materials and introduce the cradle-to-cradle concept for thermoset-based plastics and composites.

- **Material-related structural design**: life cycle assessment studies of environmental emissions have demonstrated the benefits of structural aircraft components made from lightweight Carbon Fiber Reinforced Plastic (CFRP) in comparison to aluminium and Glass Laminate Aluminium Reinforced Epoxy (GLARE), expressed in fuel consumption and CO_2 emissions and taking into account their “cradle-to-grave” emissions. Besides increasing the amount of composites in the airframe structure, further weight and fuel burn reduction can also be achieved by further optimising current composite structures in terms of cost and performance.

- **Unconventional fibre lay-ups / elastic tailoring**: lighter composite structures can be obtained through improved local directional stiffness properties. This can be achieved by local elastic tailoring of structures using advanced fibre placement, in combination with advanced design, analysis and optimisation methods, including “as-manufactured” material details in the design loop.

- **Windowless cabin**: aircraft windows in the passenger cabin and cockpit contribute to weight and drag. A radical solution to reduce weight might be replacing the windows with lightweight low-power-consumption screens with passenger-selectable views. This technology would mean that unusual aircraft configurations such as BWB and flying wings could be considered.

- **Thermoplastic composites**: most carbon fibre composites contain thermoset polymers (mainly epoxy) for the matrix material. To enhance damage tolerance and toughness, thermoplastic polymers can be used, which can be heated, melted or softened, reshaped, and then cooled to a final hardened shape, making them easy to rework and repair.

- **Nano-technologies for improved material properties**: further improvement of carbon fibre composites properties, in particular their brittleness and fracture sensitivity, can be achieved by nano material additives such as graphene platelets or carbon nanotubes. Strength, stiffness and resistance to fatigue crack propagation gains of several orders of magnitude have been demonstrated. Moreover, the significantly improved electrical conductivity of the composite materials overcomes the need for lightning strike protection systems usually achieved by copper or bronze meshes inserted in the laminate.

3.2.3 Interdisciplinary and integrative technologies

- **Large integrated panels' production**: composite materials and their related manufacturing technologies provide technical and economical enablers for new aircraft configurations. Larger, integrated structural elements with curved shapes can be realized using CFRP. Although some experience has been achieved over the last 20-30 years, efficient production in terms of tooling and procedures remains to be developed. Automated fibre placement and filament winding has enabled advanced, economically viable manufacturing of composite material structures, but for one-shot composite components, the final assembly line process must be adapted to composite materials, which have less ductility and higher stiffness.

- **On-Line Aircraft Health and Usage Monitoring**: aircraft operational behaviour can be improved through efficient damage and fault detection, maintenance, and logistics. For this, real-time assessment of the composite structure by integrated strain monitoring systems, based on networks of fibre optic sensors, can be applied. A better understanding of structural behaviour during flight may lead to a reduction of drag losses by using strain readings to adjust deformation during flight or to improve the safety margins used in the design process. Strain readings from critical parts of the structure could monitor damage or damage growth during flight. This information could be used to develop an integrated aircraft health and usage monitoring system, which enables the overall aircraft state to be assessed. Such a system would require high reliability, intelligent sensor data gathering, sensor fusion and analysis, and the development of appropriate action procedures.

3.3. Promising aircraft configurations

The five aircraft configurations that are presented hereafter are considered as catalyst for break-through: the Blended Wing Body and Prandtl wing are potential solutions for commercial transports, while advanced tilt-rotors will improve access to city centres and offshore platforms. Finally, personal aircraft and supersonic transports are assessed.

3.3.1 Blended Wing Body

Today's classical aircraft configurations feature separate structures for providing lift (wings) and carrying the payload (fuselage). This results in a heavier structure, additional wetted surface and associated viscous drag. The flying wing configuration is recognized as the most efficient aerodynamic solution, but presents challenges in many other areas. The blended wing body (BWB) presents a good compromise. Its higher structural complexity could be mitigated with development of advanced composite materials and production processes. The BWB also provides good potential for larger, more comfortable passenger cabins and new storage solutions for baggage, cargo and fuel.

3.3.2 Prandtl Plane

For a given wing span and lift, the Prandtl-type biplane, with wings connected at the tip, provides a theoretical induced drag reduction of about 20% during low-speed phases such as take off, climb, descent and landing. Such a configuration might be an interesting solution for short take-off and landing short-range aircraft with less range than today’s Airbus A320 or Boeing 737. The potential benefit of this radical change in configuration might be a reduction of up to 10% in fuel burn, as long as weight is not increased compared to a conventional aircraft. This concept provides also new solutions for engine integration.

3.3.3 Tilt-rotor aircraft

Tilt-rotor aircraft combine the hover advantages of helicopters with the higher-speeds of turboprop aircraft, overcoming the problem of helicopter speed being limited by the loss of main rotor efficiency at higher forward speeds. The next generation of tilt-rotors will feature a partially tilted wing to improve rotor efficiency at hover. A 20-passenger aircraft would have higher range than the BA609 at a cruise speed of around Mach 0.5 - close to that of modern turboprop aircraft. Depending on the regulatory situation, civil tilt-rotors would operate as commuters between medium/large cities and for offshore oil & gas plants, or long-range strategic-air reconnaissance applications.

3.3.4 Personal aircraft

For personal air transport, short-range small aircraft provide the lowest emissions and easiest handling. Such aircraft would be operating along with others at lower altitudes and speeds. An aircraft with up to eight seats could be powered by an electric main engine and have all-electric systems with blown wing concept or distributed propulsion. High level of automation and pilot assistance would be required.
The characteristics of such aircraft are reduced acquisition cost, reduced weight, reduced fuel consumption, increased reliability, reduced support equipment, simpler maintenance, expanded flight envelope, and improved survivability.
The concept requires the resolution of a number of major technology issues, however, including electromechanical actuators, environmental control and ice protection systems, and engine technology.

3.3.5 Supersonic aircraft

Supersonic business transport: although this type of aircraft does not pave the way towards a greener air transport, the current wave of globalization unquestionably creates a business regarding rich and busy people all around the world. Linking the growing business metropolises in North America as well as in Europe, Asia and South America with supersonic business aircraft could provide a more realistic business case than charter and scheduled travel.

3.4. Recommendations on priority research axes for future aircraft technologies and configurations

Recommendations on priority research axes to pave the way forward for aircraft are summarized and expressed according to research investment and respectively timeframe in **Fig. 1** and aircraft type in **Fig. 2**.

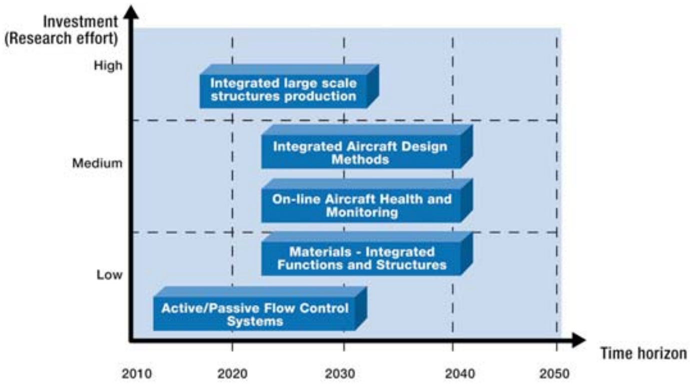

Fig. 1. Key technologies for innovative configurations

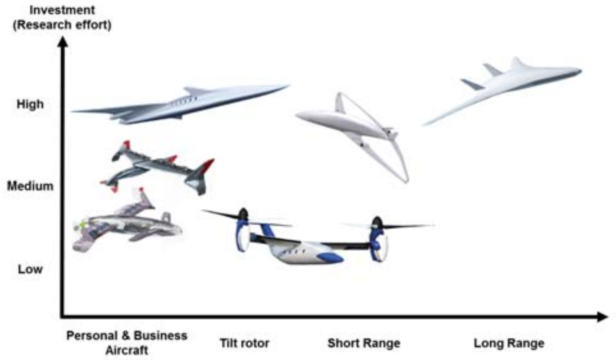

Fig. 2. Key aircraft configurations for fostering innovation

4. Propulsion

The turbofan engines powering today's aircraft are approaching their optimum in terms of efficiency and only major changes in aircraft configuration and propulsion concepts will bring step changes in fuel burn and emissions.

While there is still plenty of scope for further improvements in turbofan technology, the major engine manufacturers and research institutions are working on a large set of radical solutions for the next generation of short/medium range transports, which account for most fuel consumption, and hence emissions. The attraction of major fuel savings is balanced, however, by significant challenges on noise, complexity and passenger acceptability.

4.1. Technologies based on classical engines

Engine manufacturers are constantly working to improve engine efficiency. Work currently focuses on raising the bypass ratio with new fan configurations, and improving the thermodynamic efficiency of the core. There is also much potential for improving the performance of aircraft piston engines.
The major promising technologies to be deeply investigated are:

- Contrarotating open rotor
- Contrarotating fan
- Intercooled sytems
- Nanotechnology
- Rotating detonation engine
- Pulse detonation engine
- Piston engine injection technology

4.2. Revolutionary technologies

A number of evolutionary technologies are being studied, covering all propulsion disciplines. Biofuels are amongst the most promising fuels in the shorter term for reducing emissions, with hydrogen a longer term possibility. Electric power in various forms is attracting increasing interest as the necessary technologies mature. For specialized ultra-high-speed air vehicles, ramjets and scramjets are under development.

4.2.1 Sustainable alternative fuels

- **Non-biofuels**: innovative ideas for non-biofuels are beginning to emerge, such as fuel produced from solid waste or from industrial waste gases like fumes produced by the steel industry containing carbon monoxide (e.g. LanzaTech[1] gas-liquid fermentation process that converts CO in alcohol which can be upgraded in hydrocarbon).

- **Biofuels**: biofuels could bring reductions of up to 15% in greenhouse gas emissions, as well as helping to secure future fuel supplies. Engine lifetime, fuelling infrastructure and fuel consistency considerations mean they would have to replace conventional kerosene with no modifications to the existing system. Assuming the CO_2 released during combustion is balanced by that extracted from the atmosphere during cultivation through photosynthesis, CO_2 emissions could be virtually eliminated. The main biofuels under consideration are biologically-obtained hydrocarbons and biohydrogen. A third generation, based on algae, is another possibility. The most promising state-of-the-art fuels are based on biomass or waste feedstock and hydroprocessed natural oils (plant oils or animal fats) - called hydroprocessed renewable jet fuels (HRJ), both certified as a 50% blend for use in aviation. These are quite close to compatibility with current engines in terms of energy density, viscosity and temperature. All of the technical details are manageable, and standardization can be achieved using mineral or bio-additives. There is, however, much to be done in the field of genetic engineering to decode and enhance biomechanisms able to deliver different sorts of biofuels, additives and lubricants.

- **Hydrogen** can be burned in a jet or internal combustion engines, or used to power fuel cells which generate electricity to drive a propeller. The high energy content per mass unit would bring significant payload and range increases, and emissions, particularly CO_2, would be virtually eliminated. Liquid hydrogen has nearly four times the volume for the same energy output as kerosene and its highly volatile nature precludes storage in the wings. Most designs therefore store hydrogen in the fuselage, leading to a far bigger fuselage volume than for conventional aircraft. The performance of a hydrogen-fuelled aircraft is therefore a trade-off between larger wetted area (and hence drag) and lower fuel weight, and this depends on the aircraft size. Complete redesign of

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[1] http://www.lanzatech.co.nz

the aircraft and of the global distribution infrastructure would be necessary and hydrogen and existing infrastructures would have to co-exist. Another challenge would be to develop sustainable supplies from industry. Liquid hydrogen at -253 degrees C requires heavy insulation of infrastructure, heat exchangers to increase fuel temperature before combusting and a totally new aircraft configuration. On an energy-for-energy basis, liquid hydrogen is considerably more expensive than fossil fuels.

4.2.2 Electrical propulsion

All-electric aircraft use electric motors instead of internal combustion engines. Power comes from fuel cells, ultra-capacitors, power beaming, solar cells and/or batteries.
Research is concentrating on development of advanced technologies such as superconducting or liquid hydrogen-cooled cryogenic motors for lightweight, high-performance motors.

- **Energy-efficient storage**: highly efficient energy storage devices could bring advances in generation, conversion, distribution and storage. Potential solutions include harvesting energy from vibrations, using thermo-acoustic engines for energy conversion, actively controlling airflows for better energy distribution, and flywheel energy storage. Energy harvesting devices can be used to capture the energy in unwanted vibrations. They include conventional, miniaturized devices as well as micro devices that use novel methods of energy conversion. Examples include micro heat engines, and micro fuel cells, both of which have power densities comparable to larger-scale power plants, as well as more novel devices such as micro-electro-mechanical systems (MEMS), piezoelectric devices, photovoltaic cells, and biologically-inspired energy conversion devices.

- **Battery power**: one of the solutions to powering aircraft with electric motors is to produce the energy on the ground and store it in onboard batteries. For large aircraft the size and weight of the batteries remains excessive. However, for smaller aircraft electric propulsion appears more accessible and has already been applied successfully in the Yuneec E430 light aircraft. Boeing has proposed combining electric propulsion and gas turbine power on the same aircraft in its SUGAR study, which could solve the issue of the large power density required for take-off.

- **Fuel cells** are becoming a viable option to power electric motors for small aircraft, and to generate electricity for the more-electric-aircraft architecture increasingly present in commercial aircraft. Fuel cells are also modular and theoretically any voltage or power can be produced by a series and/or parallel configuration of stacks of cells. Technologies under consideration include the advanced proton exchange membrane (PEM) and solid oxide fuel cells. The possibility of using a PEM fuel cell stack providing the total power needed by the engine and all the auxiliary systems has been demonstrated in light aircraft, using commercial fuel cell and power management technologies, albeit with reduced speed, climb rate, range and payload-carrying capability. The major challenge is to reduce the size of the electric drive propulsion system (mainly fuel cell, motor and power management system) and to increase efficiency.

- **Photovoltaic fuel cells** are a promising technology especially for high-altitude long endurance unmanned air vehicle and small aircraft. To be competitive, costs need to be reduced by up to a factor five. At present most of the solar cell market is based on crystalline silicon wafers, but there is now major interest in thin-film solar cells with film thicknesses in the range of 1–2 µm which can be deposited on cheap substrates such as glass, plastic or stainless steel. The development of suitably light, powerful batteries is still several decades away. Solar-powered aircraft powered solely from the heat provided by the sun are being tested, but clearly would not be suitable for 24-hour deployment.

- **Hybrid electric turbines** would use the excellent thrust–to-weight ratio of a turbine engine for high-power requirements such as take-off and electrical power for cruise and descent. Cycle analysis has shown that a good compromise could be to install a 4MW electric motor on the low-pressure (LP) shaft. The additional power would be activated during cruise to reduce the power demand on the LP turbine. A simple cycle simulation shows that when 50% of the power required to drive the fan is provided electrically, specific fuel consumption falls by 21%. The ratio of jet fuel to batteries depends on the mission. Short-range flights would use more battery power, while long-range missions would be mainly kerosene-fuelled. The required electric motor and battery performances are currently unavailable, but could be within the 2050 timeframe.

4.2.3 High-speed propulsion

Research on high-speed aircraft capable of reducing long-range flights to between two and four hours has been ongoing for several years. Speeds of Mach 4 – Mach 8 are necessary, at altitudes from 24km – 30km, which point towards advanced high-speed airbreathing engines such as ramjets and scramjets.
Within the European Union’s Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT I and II[2]) project, theoretical and experimental studies on the design of two high-speed concepts, equipped with dual-mode airbreathing and hydrogen-fed propulsive systems, are being performed in order to demonstrate their feasibility for long-haul flight.

- **Low NO_X combustor ramjet**: combustion of the air-hydrogen mixture required for the pre-cooled LAPCAT II ramjet engine results in high levels of NO_X production, with a resulting unacceptable effect on the ozone layer. The thruster-combustor design is therefore critical to the future of this concept. Rich-burn, Quick-mix Lean-burn (RQL) combustion appears to be promising. It involves two-stage combustion in which all of the fuel is injected in the first stage, reacting with a fraction of the airflow and resulting in a fuel-rich mixture. In the second stage the remaining air is mixed with the main flow and reacts with the remaining fuel in a fuel-lean combustion process.

- **MHD scramjet**: a strategy for improving supersonic combustion ramjet (scramjet) performance could be based on the Magneto-Hydro-Dynamic (MHD) bypass system. MHD scramjets promise increased combustion efficiency and stability, with more compact design of the scramjet propulsive system. Feasibility has still not been demonstrated, however. Combustor efficiency is critical to overall thruster performance and there remains doubt as to whether the concept is possible without excessive aerodynamic drag.

4.2.4 Alternative configurations

New materials and manufacturing technology are increasing the feasibility of new aircraft configurations, such as the Blended Wing Body aircraft, opening possibilities for major powerplant installation improvements bringing significant reductions in fuel burn and emissions.

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[2] http://www.transport-research.info/web/projects/project_details.cfm?ID=37390

- **Embedded propulsion**: distributed and embedded propulsion places the engines where they can partially or totally ingest the airframe boundary layer, reducing drag and making the downstream flow of air more uniform. A BWB configuration distributes thrust generation along the wingspan by using several embedded, or buried, small engines. Propulsion can come from two or more engines. Ideally, a higher number, ingesting the entire boundary layer, would be used. Poor fan performance at the boundary layer indicates an optimum of three or four engines and two conventionally-mounted engines. The baseline is a conventional turbofan, but with a gearbox to reduce engine core size and low-pressure turbine size. The core engine is then used to mechanically drive the three fans which, for a 300-passenger aircraft would have a diameter of 1.2m. The lower weight and noise and higher aerodynamic efficiency of this solution could produce a potential 54% fuel burn reduction, noise levels 46 EPNdB below ICAO Stage 4 and NO_X emissions 81% below CAEP 6. Economically, small engines have lower development, production and maintenance costs. Also, because the necessary thrust would be achieved with a number of equally-sized small engines it might be expected that only a few small engine types would need to be developed, which would open the production and maintenance markets to a wider, more competitive market.

- **Solar energy to improve combustion**: the BWB configuration offers an opportunity to cover the upper wing surfaces with photovoltaic elements. A technology breakthrough would be solar cell paint, and some concepts have already been developed and demonstrated. Such a layer, applied to the carbon fibre materials from which the wing would almost certainly be built, would have the additional advantage of improving the electrical properties of the airframe as well as increasing resistance to lightning strikes. The electrical energy from the solar cell paint would be converted into high voltage/low intensity pulses which would be applied inside the combustion chamber to increase the enthalpy of the gas impinging on the high-pressure turbine, increasing the thermodynamic efficiency of the engine core.

4.3. Recommendations on priority research axes for propulsion

Recommendations on priority research axes to pave the way towards 2050 propulsion are summarized and expressed according to research investment and respectively timeframe in**Fig. 3** and aircraft type in **Fig. 4**.

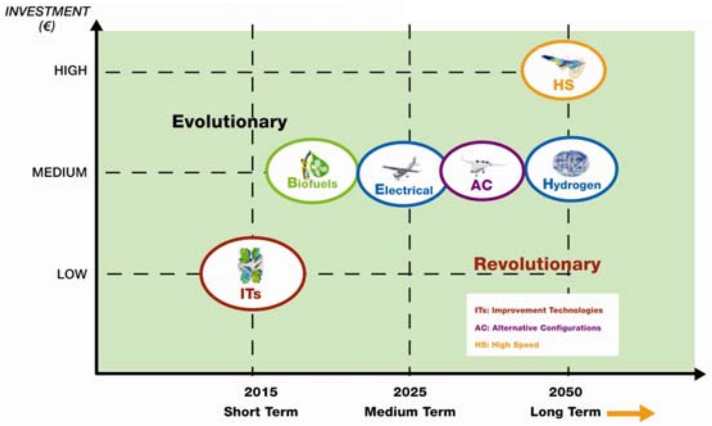

Fig. 3. Roadmap towards 2050 propulsion

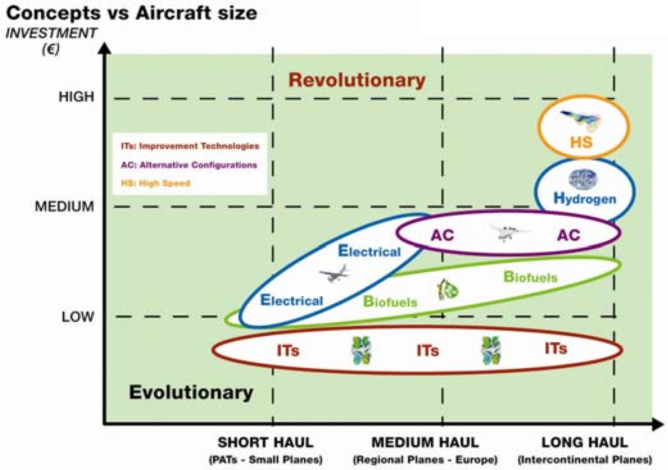

Fig. 4. Key innovations versus research investment

5. On board subsystems

Aircraft subsystems provide functions for the crew, passengers, aircraft and air traffic management system. Because they involve many fields of expertise and technology, a full list of potential solutions for the subsystems of 2050 is likely to be incomplete. Research which can realistically contribute to the 2050 goals will therefore be characterized more by evolution than by revolution.

The term "subsystem" is mainly related to one or several interacting electric, electronic and electro-mechanical on board equipments which support "system" functions or pneumatic/hydraulic equipment related to on board actuation systems.

The study was based on top-down and bottom-up approaches:

- Top-down approach: high level goals analysis and investigation of the needs within the other domains of this study;
- Bottom-up approach: existing aircraft systems analysis aiming at any possibilities for radical improvements.

5.1. Top-down approach

The main areas for the development of on board subsystems that have been identified are the following ones:

- **All-weather all-time flight**: systems which support the pilot, or in unmanned vehicles, the autonomous flight management system, to fly in all-weather conditions at all times require on board presentation of meteorological data and the technologies necessary for enhanced and synthetic vision to support flight in low-visibility conditions.

- **Data-links**: a large increase in high-speed data link usage is foreseen, which will require on board subsystems technology. Important aspects are the increasingly stringent requirements on safety (integrity, reliability, availability) and robustness

- **Revolutionary energy technologies**: Revolutionary new ways of supplying energy to the aircraft will require on board subsystems technology in many areas. Apart from reducing the energy consumption or environmental footprint of individual systems and of the complete aircraft, areas of interest include: efficient, power-dense and recyclable energy storage systems, energy generation and energy control/management.

- **Advanced health monitoring and prognotics**: reduction in aircraft life cycle costs, and that of on board systems, can be achieved by improved maintenance, supported by aircraft health-monitoring systems. These enable long-term scheduled maintenance to be replaced by on-condition-based maintenance.

- **Meta-systems**: the ever-increasing complexity of systems and functions brings a need for research into effective and reliable meta-systems which process and interpret the data of many systems at a higher level. A combined flight management system for manned and unmanned aircraft can be foreseen, which shares decisions between the navigation system and the ground operator.

- **Systems engineering**: methods, processes and tools: development and certification of new aircraft subsystems involves meeting safety and reliability requirements, calling for methods, processes and tools relevant to systems engineering rather than technology development. The development of sophisticated tools supporting the development process will be as important as the development of new technologies.

- **Standardization and modularization**: for technology development in general, open systems and standards are important building blocks that allow modularization. Here, a role is seen especially for research institutes because of their independency. While standardization is not in itself expected to be useful as a stand-alone research topic, each topic should have standardization as a goal.

- **Adaptive, reconfigurable, multi-purpose hardware**: one of the challenges will therefore be to enable basic hardware to be reconfigurable, so that it can implement different functions, depending on the flight phase. For non-safety-critical equipment, the weight and volume of dedicated electronic equipment will be replaced by basic, "general-purpose" electronic boards.

5.2. Bottom-up approach

From the bottom-up perspective, the development of a new aircraft subsystem has to satisfy safety and reliability criteria if it is to achieve certification. Such requirements call for methods, processes and tools relevant to systems engineering rather than to technology development.

The development of sophisticated tools supporting the phases of a development process - design, verification, testing, etc - will be as important as the development of new technologies. The applicability of new technologies will be conditioned by the availability of processes and methods to certify the related equipment. As an example, there is the possible use of artificial intelligence to achieve for full autonomy. Nowadays, functions using artificial intelligence cannot be certified because of their unpredictability. If we do not elaborate new ways to state the reliability, and consequently the safety, of such new paradigms, technologies based on them will no be useable. Technologies alone are not enough. In parallel, system engineering methods and tools have to be developed in order to apply those technologies in the aeronautical environment.

Further to the main areas of research defined within the top-down approach, an overview of research topics defined following the bottom-up approach is proposed below within a non-ordered list:

- Reconfigurable communication systems
- Adaptive communication systems
- Conformal antennae
- Enhanced and Synthetic Vision Systems
- Vision-based UAV taxiing and auto-landing
- Fuel cells for auxiliary power unit
- Powerline data communication in aircraft
- Wireless in-aircraft data communication

6. Towards full automation?

The ever more complex air transport system facing more and more ambitious goals is naturally evolving towards automation. Whatever the degree of automation, the air transport system will continue to comply with its key performance areas: service level, environment, safety and security, increased capacity, airline cost, flexibility and predictability. The aim here is to define the biggest challenges in the path towards a high level of automation. Although this may lead to *full* automation at some points, full automation is not a goal on its own. Automation is merely a means to improve the above performance areas.

A highly automated air transport system is based on three pillars: the 4-dimension contract, automated air traffic management and automated aircraft.

Enabling technologies paving the way towards full automation are already being studied, but many are still at low operational levels. Naturally, the shift towards full automation will not happen overnight, but will rather be an evolution in which more and more tasks are executed by automated systems.

6.1. Developing realistic models

Creating sufficiently realistic models for research is a major challenge as systems become more complex and interactive. The biggest challenge lies in testing the interaction between elements of the system. New modelling techniques and methods to validate models will be necessary to build the air traffic management (ATM) system of the future. Standardized models that allow coherent and comparable testing at different sites would be a major step in ATM simulation. As different models could be compared more easily, the development cycle of new techniques could benefit as decisions about the most promising techniques become much easier.

6.2. Human-machine interface

The main challenge in designing a next generation human-machine interface (HMI) for ATM is deciding which information not to present. As the potential amount of information will be huge, only information that is necessary for next-generation controllers to execute their tasks should be presented. Advanced monitoring tools will be necessary to verify if the planning is properly executed. In case a problem arises that cannot be solved by the automated tools, the ATM manager will need to be brought in the loop by presenting the right information such that he can make a deliberate decision

6.3. Interoperability and data collection, data mining

The path towards full automation puts high demands on the timely availability of the right data in the right place at the right time. As the current ATM system consists of a huge number of incompatible systems, interoperability is a major challenge. Systems will need to be interconnected and data should be shared and made available among stakeholders using standardized protocols and formats.

As more and more systems become interconnected, it is important to be able to locate and extract the right information. New data-mining algorithms are needed to support data extraction and selection.

6.4. Sensor fusion

Current onboard and offboard sensors provide a wealth of information. Often this information is (partially) overlapping. Sensor fusion aims to combine the various sensor information sources to provide a single, optimized, view of the world. For the future, innovative sensor fusion algorithms need to be developed which are extremely tolerant of any system failure. Situational awareness must be guaranteed in all weathers conditions, all times.

Innovative sources of data will be created which offer accurate weather forecasting before and during the flight. New Synthetic Aperture Radar technologies, molecular/optical air data sensors and multiple magnetometers for advanced attitude determination will have to be developed. Such technologies will enable fully automated operations with low cost, weight and size. However, more onboard computational power will be required for real-time implementation

6.5. 4-dimension contract

The 4-dimension (4D) ATM contract is the central operational concept enabling the global optimization of air traffic management. It provides the framework for automatic handling of the flight management of all air traffic participants by a central ATM system ensuring safe separation and optimization of all flights, according to global performance criteria.

A 4D contract can be represented as a time dimension moving along with a three-dimensional airspace tube assigned to each aircraft by the ATM system and/or negotiated by the aircraft themselves. All aircraft must stay within their assigned 4D volumes (i.e. respect their contracts) for the entire duration of the flight. As long as they do so, they are guaranteed conflict-free trajectories and the entire air traffic system is globally optimised to the extent of the capability of the central system. All 4D contracts are generated by the central ATM system (strategic planning). Each contract is issued for the entire flight, including ground operations, and is conflict-free in relation to all other contracts. The aircraft are in charge of executing their contracts and the ground system monitors them. Under certain circumstances, such as emergencies or off-nominal situations, the contract can be updated on-board the aircraft (dynamic planning).

The implementation of a 4D contract-based ATM system will bring significant improvements to ground and on-board systems, both on technology and conceptual levels. However, the 4D contract robustness against ATM uncertainties is still to be quantified.

6.6. Emergency handling

Today, flight procedures are subdivided into normal, abnormal, and emergency situations.

In a highly automated environment, systems should contain built-in rules to handle abnormal and emergency situations. Statistics indicate for more than half of all aircraft accidents as reason human error, so it is reasonable to ask whether the system itself or the responsible human-in-the-loop manager should respond to abnormal situations.

Aviation systems are usually designed as human-assistance systems which provide advisories to the operator. In the future, fully automated systems will decide and execute actions, and the operator will have a managing and supervising task. If an error occurs, the human will be able to intervene to solve problems the system is not able to solve.

A high level of automation will enable more systems to be operated with fewer humans (i.e single pilot cockpit, Single European Sky), although this will reduce the situational awareness of an operator for a particular emergency. If humans are supposed to handle these situations, it is essential to identify how the operator should focus on it in an efficient and safe way.

6.7. Recommendations on priority research axes towards automation

Recommendations on priority research axes to pave the way towards future highly automated air transport system 2050 are summarized in the roadmap below (**Fig. 5**).

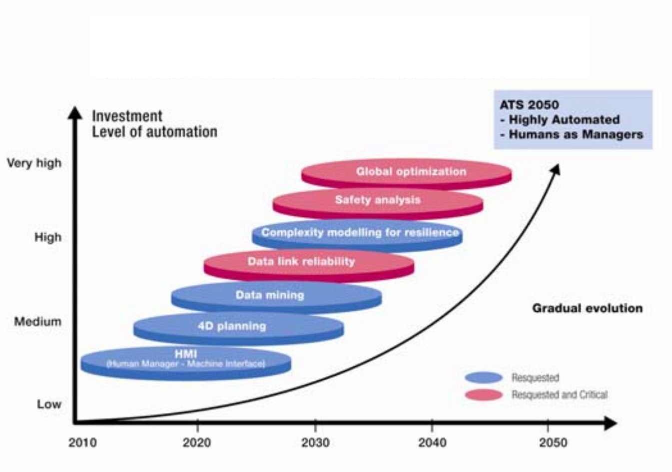

Fig. 5. Key research axes toward automation

7. 2050 Airport

The airport of 2050 must be driven by the dual requirements for increased capacity and improved efficiency while being customer orientated [1]. Airport location, layout and equipment will take into account environmental concerns as well as passenger comfort. Airports must also function with the highest possible levels of safety.

7.1. General concept of the 2050 airport

The following are seen as critical elements:

- Air traffic management will be related to a network of airports rather than local and individual airports;
- Landside and airside components need to be re-thought and intermodal means of transport described.

The airports of 2050 will be integrated into a network of air, ground and even water transport that will enhance capacity and make transportation more efficient. The airport network will be mainly composed of hubs connected to secondary airports that will provide services to a greater number of users and operators. By 2050, the Single European Sky (SES) four-dimensional (4D) air traffic management system will have been fully implemented. It will be important to provide airport networks with the capability to coordinate/ manage ground operations with 4D airborne operations.

Within this timeframe, several scenarios can be envisaged:

- Commercial aircraft to or from hubs. Passengers have access to airports using the intermodal transport system;
- Personal transport systems to or from secondary dedicated airports connected with the home by air-rail transportation;
- Hub and secondary airports connected, enabling passengers using personal aircraft to reach the hub and transfer to commercial aircraft.

Connections between hubs and secondary airports will be possible by means of efficient and environmentally friendly public transport, but will also include an optimised network for private transportation that will enable the efficient, safe use of personal ground transport. Ships may be used to connect secondary airports, depending on their location.

Air transport will include current-configuration aircraft, plus other actors such as personal air transportation vehicles or aircraft with passengers pre-loaded into standard fuselage boxes. In addition, different types of runways as well as take-off and landing assistance systems will be available to provide services for conventional take-off and landing aircraft, short-take off and landing air vehicles or convertible vehicles.

Airport networks should be designed to accommodate them all.
Interconnections within this network will be provided by multimodal transport, including high-speed trains for the national or international network, trains, subways, tramways or suburban trains at regional airports, electric ground vehicles, environmentally friendly ships or even air-buses.

7.2. 2050 Airport operations

By 2050, the Single European Sky (SES) four-dimensional (4D) air traffic management system will have been fully implemented. It will be important to provide airport networks with the capability to coordinate and manage ground operations with 4D airborne operations.

An integral element of the airport of the future is the handling of information and the collaboration of all involved stakeholders. Total Airport Management (TAM) will be expanded, the role of operators changing from tactical to pre-tactical and from specialized controlling functions to multi-system management.

In the short term, the airside will take advantage of improvements resulting from the SES programme and will evolve towards higher automation. The airport infrastructure will include revolutionary architecture adapted to any new aircraft configuration and propulsion mode (i.e blended wing body and new fuels, such as hydrogen or biofuels).

As capacity of the current airport systems is often a limiting factor, new approaches are made to tackle these. Completely new runway layouts and locations (remote at sea, large surfaces enabling operations from any direction) or new operational procedures (formation flying, multiple approach paths) are possible solutions.

To achieve the goals of reductions of emissions ground operations are tending to use electrical energy for ground movement of aircraft (autonomous and automated taxi systems connected to the aircraft) and all ground handling equipment.

7.3. A passenger-oriented airport

The 2050 airport will use new technologies to make passengers' stay in the airport as short and comfortable as possible. One of the most important challenges will be achieving public confidence in automation, although this will demand significant advances in technology.
Automation will mean that users are informed about the current status of their journey and alternative options, periodically or on demand. Information points will be distributed around

the terminals and interactive devices embedded in transport systems so that passengers can access travel information at any time using smart phones or interactive panels/screens situated along the intermodal transport network.

7.4. The airport as the heart of intermodality

A major goal for the future intermodal transport system is to reduce dependence on the automobile as the major mode of ground transportation and increase use of public transport, especially in the case of the future air transport system (**Fig. 6**).

Underground railway stations built below terminals reduce the need for private cars as well as limiting the environmental footprint.
Intermodality can be envisaged at several levels, from local public transport to international connections:

- City centres and suburban areas have to be accessible using the tramway or subway connecting with railway stations located on the airport landside
- At regional level, connections to a high-speed train is a strong advantage for an airport's attractiveness if it is rapid and serves the nearby cities
- For national / international connections
  - Integration of airports within a regional/national railway network or other future modes of public transport
  - National railway stations at airports must be part of the landside, where the passenger journey starts with passenger check-in and luggage deposit
  - High-speed train connections to connect regional megacities
  - Connections between regional airports to major hubs with high-speed train as an alternative to short-haul air services, releasing slots and relieving airport congestion

The airport landside should provide inter-terminal shuttles to provide convenient, fast and reliable services for the passenger and luggage. Automatic subway trains and/or tramways should be considered instead of buses.

In the door-to-door approach, the airport landside is enlarged or redefined:

- Railway stations are part of an extended 'landside'
- The journey starts anywhere in the public zone
- Security checks and luggage registration/deposit are done in the railway station, on board a train or in dedicated points in a city
- Quick & easy checking using, for example, biometry
- Luggage transportation from home to the terminal/plane (or door to door) is available

The subway or railroad serves all the terminals/gates: long walks are no longer needed to reach any point in the airport (especially with underground terminals)

Fig. 6. The 2050 airport as the heart of intermodality

8. Conclusion

The EREA vision on 2050 air transport system aims at giving recommendations on priority research axes to be carried out in Europe during the next decades if we want to pave the way towards an ambitious future system as advocated by the European Union. This vision does not pretend to predict the future; it rather provides keys to build our future.

Acknowledgment

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This study, briefly summarized here, gathers knowledge and expertise of almost 50 researchers and engineers. It is worth noting that detailed technical reports on the five domains, aircraft configuration, propulsion, on board subsystems, automation and airport, are available upon request to the authors.

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[1] European Union *Flightpath 2050 - Europe's Vision for Aviation*. EUR 098 EN, 2011.

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