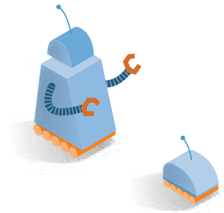
Association of
European Research Establishments in Aeronautics

EREA FUTURE OF AVIATION

The research and developments



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Summary

The "EREA Vision Study – The Future of Aviation in 2050" is the update of the previously released "EREA vision for the future –Towards the future generation of Air Transport System" published in 2010. This new study, describing EREA's own vision, has as objectives: (i) to share EREA's vision with external stakeholders to help enhance cooperation; (ii) to form the basis for EREA to support policy makers at national and European level; (iii) to motivate EREA and its members to work together to common and ambitious goals; and (iv) to engage with the general public, particularly on societal needs and sustainability for the aviation sector.

The outcome of the study is presented in two parts:

- a first document, which describes the current societal and aviation context and imagines four alternative future scenarios for 2050, exploring how aviation could contribute to each scenario ;
- a second document, which provides the technical overview of the research and development (R&D) activities needed to realise EREA's vision for the Future of Aviation.

In this, the second document, technologies which will enable the four future scenarios are presented. These technologies were identified in a series of workshops by a range of EREA experts in the autumn of 2020.

Although the four scenarios are all different, they result in a set of common themes for research concerning the future of the air transport system. Those themes are:

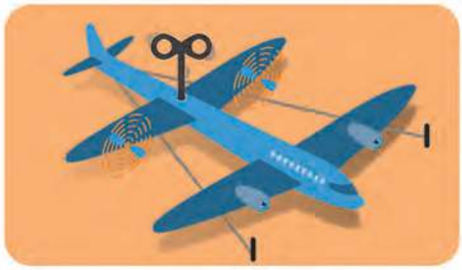
- diversification of vehicle configurations;
- a wide range of energy sources and propulsion systems;
- variety of high performance, smart, and sustainable materials, certified for use in aeronautical structures, engines and systems;
- implementation of automation and autonomy in every aspect of aviation operations and throughout the entire life-cycle of air vehicles;
- application of risk-based techniques to ensure that aviation remains the safest and most secure mode of transport;
- highly resilient infrastructures for position, navigation, timing and communications, as well as for environmental monitoring, safety and security;
- maintenance, repair and overhaul (MRO) based on predictive approaches;
- passenger-centric systems for journey planning and security screening.

Differences in the scenarios also highlight areas of uncertainty, resulting in **contrasting themes**. For those themes, research might or might not be important in the timeframe to 2050, depending on how the world evolves. These contrasting themes include the implementation of urban air mobility and the transition to a true, zero emission and sustainable aviation.

Finally, a number of **key enablers from outside of the aviation sector** are also indicated, which are necessary to complement or enable the aviation-specific developments in its priority areas.

[1] *https://www.erea.org/erea-vision-study-future-aviation-2050*

The Research and Developments for the Future of Aviation

	
Diversification of vehicle configurations	A wide range of energy sources and propulsion systems
	
Variety of high performance, smart, and sustainable materials, certified for use in aeronautical structures, engines and systems	Implementation of automation and autonomy in every aspect of aviation operations and throughout the entire life-cycle of air vehicles
	
Application of risk-based techniques to ensure that aviation remains the safest and most secure mode of transport	Highly resilient infrastructures for position, navigation, timing and communications, as well as for environmental monitoring, safety and security
	
Maintenance, repair and overhaul (MRO) based on predic-tive approaches	Passenger-centric systems for journey planning and security screening

About this study

This study has created EREA's vision for the Future for Aviation in the year 2050. This Future is used to understand the potential impacts on aeronautical research and development (R&D) activities. The study was performed in the context provided by Flightpath 2050[2], describing Europe's vision for aviation alongside the more detailed strategic research and innovation agenda[3] (SRIA) developed by the Advisory Council for Aviation Research and Innovation in Europe (ACARE).

The complete study is presented in two documents:

- a first document, which describes the current aviation context and imagines four alternative scenarios for how the world could look in 2050;
- this second document, which addresses the specific trends, technologies, and research themes that would be needed in each scenario defined in the first document.

The combination of the two documents will direct EREA to synthesise a coherent roadmap for research activities to 2050.

Aviation is a vast subject that incorporates many different definitions often for the same terms; the definitions used in this document are those that align most closely with EREA's mission in civil aeronautics. In particular, throughout this study, **Aviation** means the **Civil Air Transport System**, encompassing the movement of civilian passengers and cargo in the Earth's atmosphere, from both private and commercial perspectives. Defence and/or space aspects are only touched upon when they are foreseen as having significant impact on the civil panorama and are not investigated in depth.

The outlook year selected for this study is 2050. Although several previous studies give a view on how aviation might evolve by 2050 or what aviation should aim at becoming in 2050, a number of significant changes in the political and societal landscape indicated the need to re-evaluate those studies and re-assess the potential range of Futures of Aviation in the light of new events.

The study is broad and non-specific in geographical scope. The scenarios can be applied to global, regional or national scales or to international blocs and could be mixed to allow for different development paths in different places.

This study is aimed at connecting and to engaging all of the different stakeholders essential for a healthy R&D ecosystem.

First, and most important, the study aims to enthral and motivate **EREA** and its individual **research establishments**, as representatives of the European Research Community. The vision has been created by EREA experts for EREA experts, in order to connect all EREA members, at all levels, from the Board to the youngest of the researchers. The vision should be used to guide EREA through the decisions which will need to be made and to inspire the EREA members.

[2] *Flightpath 2050, Europe's Vision for Aviation, Report of the High Level Group on Aviation Research, https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf*

[3] *Strategic Research and Innovation Agenda, ACARE, https://www.acare4europe.org/sria*

Second, this study enables the EREA vision to be presented to its **external stakeholders**. Several groups are active in Europe, with the common interest of maintaining European aviation's competitiveness, safety and security, whilst minimising negative environmental impacts and maximising positive socio-economic benefits. These groups include ACARE, the Clean Sky Joint Undertaking, the SESAR Joint Undertaking, the European Aeronautics Science Network (EASN) and others. Even though there is a shared purpose, multiple voices with different emphases may hinder even the most robust of messages. By sharing its vision, EREA hopes to create a platform for dialogue to reach a single, communal vision and boost cooperation.

With a strong, coherent and common vision, EREA and its stakeholders can then approach policy makers at national and European level to support their decision-making process, as a credible, coherent, independent and trustworthy voice. Engaging **policy makers** and government bodies will ensure that R&D outcomes are not confined to laboratories and academic publications, but are used practically and effectively in a broad, multi-interest environment to maximise positive socio-economic and environmental impact.

Finally, this study desires to engage the **general public** by showing that EREA and its members have an ambitious vision which can ensure a thriving aviation industry without compromising on societal needs and sustainable development goals[4]. The study shows the public that their concerns are also EREA's, and that research choices will be made together, towards a common goal.

[4] *https://sdgs.un.org/goals*

Setting the scene

...on the Scenarios

The four scenarios that underpin EREA's vision were the outcome of a series of workshops performed in the spring of 2020 and attended by EREA members experienced in scenario thinking and future strategy. The scenarios, and hence this vision, should be seen as the opinion of EREA experts, from different technical and cultural backgrounds, all functioning at the interface of different spheres of influence: academia, industry and government.

The scenarios have been built on the 2020 context and on identified trends in civil aviation and in various social, economic, and political factors, to imagine four alternative future worlds and the contribution that aviation could have in those worlds. The full details of development of the scenarios and the detailed descriptions of each, are available in the first document[5].

None of the scenarios is designed to be absolutely realistic, but they are the vehicle for exploring options and ideas. No value judgements have been implied or made, so no one scenario shall be perceived as "better" than any other in absolute terms, although the reader will obviously have a personal preference.

These scenarios are used in the following sections of this document as the basis for EREA to chart its future technological, policy and infrastructure roadmaps, allowing to consider a wide range of potential future eventualities.
A summary description of the scenarios is provided in the table in the next page, as reference.

... on the Research Themes

In 2012 EREA published "From Air Transport System 2050 Vision to Planning for Research and Innovation"[6]. In that document, the research needed to pave the way for the future of Air Transport System in 2050 described in "EREA: vision for the future – Towards the future generation of Air Transport System"[7], published in 2010, was presented.

Five priority research areas were included in that document:

- Vehicle Configuration
- Propulsion
- On Board Subsystems
- Towards Full Automation?
- Airport

Given that the 2012 document was in large part influenced by the 2010 EREA scenarios and by Flightpath 2050[8], an update of the research topics was deemed necessary.

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5 *EREA Future of Aviation – The Scenarios, 2021*

6 *From Air Transport System 2050 Vision to Planning for Research and Innovation, the Association of European Research Establishments in Aeronautics, May 2012, https://www.erea.org/sites/default/files/pdf/Total%20Study%20Dokument.pdf*

7 *EREA: vision for the future –Towards the future generation of Air Transport System, the Association of European Research Establishments in Aeronautics, October 2010, https://www.erea.org/sites/default/files/pdf/EREA_2010_WEB.pdf*

This current study supplements the "Future of Aviation – The Scenarios" by providing the technological aspects supporting the scenarios of the future of the air transport system. In each of the scenarios developed in this study, the emphasis is given to the technological topics which will characterise aviation and its research ecosystem in 2050.

Those technological topics have been identified during a series of online workshops and interviews in the autumn of 2020.

Once the four scenarios had been developed, EREA experts in different technical disciplines were asked to indicate what technologies and research topics would be present in each scenario or would be needed for the scenario to actually become a reality.

The following questions were asked during the workshops:

- How do we fly in this scenario?
- Which research fields affect this scenario?
- What opportunities does this scenario offer you/your research topic/research in general?
- Which existing research/innovations has not yet been implemented but would enable or fit into this scenario?

The answers helped to define the details of the aviation ecosystem and the research environment in each scenario.

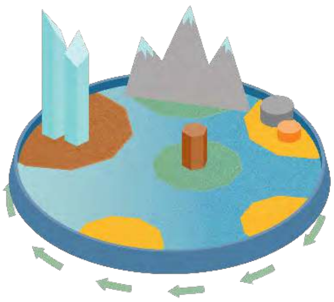
Specific technologies were grouped into four research areas:

- Vehicle;
- Propulsion;
- Systems;
- Operational Infrastructure.

For each scenario, a summary of the technologies, characteristic of that scenario, is given.

These technological scenarios will be used as the basis for EREA to chart its own up-coming technological, policies and infrastructure roadmaps, allowing to consider a wide range of potential future eventualities.

The Scenarios for the Future of Aviation

	**Mad Max** ...aviation: a luxury for the few in a world of consumerism, challenges and conflict	*A world characterised by deglobalisation and fragmentation; extreme nationalism and populism; instability; protectionist economies; high levels of inequality; low sustainability; climate crisis; low levels of R&D.* *Aviation is an expensive, luxurious and highly desirable product but is unreliable due to climate change and different sources of instability. There are few industrial players with no innovation and limited R&D.*
	**Tech for You** ...aviation: side by side alternative technology in islands of choice, competition, and customisation	*A world characterised by multipolarity and competition; high-cost, low economy-of-scale production offset by widespread automation; market driven by consumer choice and desires; free market economies; high R&D with national and short-term focus; different approaches to and meaning of sustainability in different islands.* *Mobility is flexible with air transport part of the local, intermodal transport system. The overall approach is to strive for door-to-door mobility.*
	**Stripping Down** ...aviation: sustainability achieved by a world of centralised command and control	*A world characterised by political stability; command economies; centralised government; prescriptive regulation; slow but stable economic growth; standardisation and uniformity; prioritised and government-directed sustainability.* *There is limited and highly controlled mobility due to high prices, security threats, flight shaming and regulation. Sustainable intermodal generic solutions are enforced. There are few industrial players due to high cost and low demand.*
	**Optimising Together** ...aviation: unlimited freedom in a world of common purpose, collaboration and cohesion	*A world characterised by unification and harmony; global cooperation and collaboration; global legal and institutional frameworks; high stability and growth; sustainability; market-driven economies and liberalisation; high standardisation and confidence.* *Mobility is growing and is fully sustainable. Different aviation solutions are available for all journey segments from UAM through formation flying to suborbital flights.*

[8] *Flightpath 2050. Europe's Vision for Aviation. report of the High Level Group on Aviation Research. European Commission. 2011. https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf*

...on the Definitions

Many of the words and phrases used in aeronautics to describe innovation, technological developments and new ways of flying, such as drone, are in common use. Other terms are used interchangeably, whereas others overlap or are unclear, such as urban air mobility (UAM) and drone. To help the reader, the following table provides the definitions of the terms as they are used in this document.

Term	Definition used in this document
(Fully) Electric aircraft	An aircraft powered (solely) by electric motors irrespective of the source of electricity, which might be batteries, fuel cells or other sources
Air traffic management (ATM)	The dynamic, integrated management of air traffic and airspace including air traffic services, airspace management and air traffic flow management — safely, economically and efficiently — through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions[9]
Air traffic services (ATS)	Services which regulate and assist aircraft in real-time to ensure their safe and efficient operations. In particular, ATS is to: prevent collisions between aircraft; provide advice of the safe and efficient conduct of flights; conduct and maintain an orderly flow of air traffic; and notify concerned organizations of and assist in search and rescue operations
Air vehicle	A machine that is intended or used for transporting people or goods in the air
Aircraft	Any vehicle, with or without an engine, that is capable of flight
Airplane/aeroplane	A powered flying vehicle with fixed wings and a weight greater than that of the air it displaces
Automation	The use of machines or computers instead of human to execute a task. Automation does not necessarily imply autonomy
Autonomy	The capability of a machine to operate and take decisions without the need for human intervention. There are various levels of autonomy ranging from the presentation of decision options by the machine to a human operator through to full decision-making authority by the machine
Battery	An electrochemical cell that uses redox reactions in a system comprising two electrodes, an electrolyte and (in the case of Li ion batteries) a separator to produce electricity. Unlike fuel cells, batteries are self-contained and do not require an external source of fuel whilst in operation
Condition based maintenance	A strategy to perform maintenance only when it is needed using deterministic models, fed by data collected by in-built sensors, to calculate one or more indicators. Maintenance is defined as required when an indicator crosses a pre-defined, static threshold, showing that equipment is going to fail or that performance is deteriorating

[9] *ICAO Doc 9854*

Term	Definition used in this document
Drone	A remotely piloted or autonomous flying machine used for many applications other than carrying passengers
Fuel cell	An electrochemical cell that uses a redox reaction, often using hydrogen fuel (the reducing agent) and oxygen (the oxidising agent), to generate electricity. The fuel cell requires a continuous supply of reducing and oxidising agents
Fully autonomous air vehicle	An aircraft that operates without any intervention or monitoring by a human operator
Hybrid electric aircraft	An aircraft that uses a combination of electric motors and jet (or piston) engines using fossil or drop-in fuels
Length of flight	• Ultrashort range: less than 30 minutes in duration (<50km) • Short range: between 30 minutes and one and a half hours in duration (50km to 1500km) • Medium range: between one and a half and four hours in duration (~1500 to ~4000km) • Long range: between four and 12 hours in duration (~4000km to 10000km) • Ultralong range: greater than 12 hours in duration (~>10000km)
Mobility as a Service (MaaS)	The integration of various forms of transport services into a single mobility service accessible on demand. MaaS[10] provides a diverse menu of transport options, be they aviation, maritime, rail, hyperloop, public transport, ride-, car- or bike-sharing, taxi or car rental/lease, or a combination thereof. A single application is used to provide access to mobility, with a single payment channel instead of multiple ticketing and payment operations
Predictive maintenance	A maintenance strategy driven by predictive analytics, for example using statistical techniques or machine learning. Data from multiple, in-built sensors is fused in a dynamic prediction model that forecasts future breakdowns
Size of aircraft	• Flying car: 1 to 4 passengers • Very small aircraft: less than 20 passengers • Small aircraft: 20 to 100 passengers • Medium aircraft: 100 to 240 passengers • Large aircraft: 240 to 350 passengers • Very large aircraft: larger than 350 passengers
Structural health monitoring (SHM)	Structural health monitoring uses non-destructive inspection principles and built-in sensors that automatically and remotely assess an aircraft's structural condition in real time and signal the need for maintenance

[10] *Adapted from the MaaS Alliance definition, https://maas-alliance.eu/homepage/what-is-maas/*

Term	Definition used in this document
Sustainability	Sustainability, as defined by the United Nations, is the reconciliation of environmental, social and economic demands (known as the three pillars of sustainability: "people, planet, profit") for the immediate and future well-being of individuals and communities
Uncrewed aerial system (UAS)	The entire system comprising an unmanned aerial vehicle (UAV), a remote system to control it from another platform, and the communications system that links the two
Uncrewed aerial systems traffic management (UTM)[11]	A traffic management ecosystem for uncontrolled operations that is separate from, but complementary to, the air traffic management (ATM) system. UTM involves concepts of operation, data exchange and continuity requirements, and a supporting framework to enable multiple, beyond visual line-of-sight (BVLOS) UAS operations at low altitudes (under 400 ft above ground level) in airspace where air traffic services are not provided
Uncrewed aerial vehicle (UAV)	As for a drone, an aircraft that operates without flight crew on-board, either autonomously or with a remote pilot
Urban air mobility (UAM)	Short-range, rural, inter-urban, peri-urban and urban applications, encompassing passenger and cargo transport, delivered by different types of air vehicle. Vehicles for UAM missions can be vertical take-off and landing (VTOL) or conventional take-off and landing (CTOL). UAM is usually provided by air vehicles with high level of flight automation, using either electric, fossil-fuel or hybrid propulsion.
U-space[12]	U-space is a set of services relying on a high level of digitalisation and automation of functions and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of UAVs. U-space is an enabling framework designed to facilitate any kind of routine mission, in all classes of airspace and all types of environment - even the most congested - while addressing an appropriate interface with crewed aviation and air traffic control. There are four levels of U-space: • U1: U-space foundation services covering e-registration, e-identification and geofencing; • U2: U-space initial services for drone operations management, including flight planning, flight approval, tracking, and interfacing with conventional air traffic control; • U3: U-space advanced services supporting more complex operations in dense areas such as assistance for conflict detection and automated detect and avoid functionalities; • U4: U-space full services, offering very high levels of automation, connectivity and digitalisation for both the UAV and the U-space system.
Vehicle	A machine that is used for transporting people or goods

[11] *https://www.skybrary.aero/index.php/Unmanned_Aircraft_Systems_Traffic_Management_(UTM)*

[12] *SESAR Joint Undertaking, https://www.sesarju.eu/U-space*

Scenario 1: Mad Max

...aviation: a luxury for the few in a world of consumerism, challenges and conflict

A world characterised by deglobalisation and fragmentation; extreme nationalism and populism; instability; protectionist economies; high levels of inequality; low sustainability; climate crisis; low levels of R&D.

Aviation is an expensive, luxurious and highly desirable product but is unreliable due to climate change and different sources of instability. There are few industrial players with no innovation and limited R&D.

How we fly in this scenario

In the Mad Max scenario, aviation is one mode in a disjointed and fragmented transport system.

The market for transport, and for air travel in particular, is polarised. For the wealthy population, flight is a luxurious lifestyle choice, as much about leisure as about necessary travel. Aviation leisure activities include space flights and cruises on luxury airships. For the less wealthy, very basic services are provided for essential journeys.

For premium travellers, the journey is seamless from home to destination. The transit to the aircraft is highly personalised depending on the length of journey. Throughout the journey, on the ground and in the air, the passenger's compartment is designed for luxury and comfort. There is full, high-speed connectivity throughout the journey supporting on-line entertainment and social media as well as business applications.

In contrast, for ordinary passengers, the journey is fragmented and can be slow and uncomfortable. These passengers make their own way to the airport using whatever means of transport is available. The comfort and connectivity within the single-class cabin can vary widely depending on the age of the aircraft, airline and service class.

The majority of air travel is domestic, short- and medium-haul, with a smaller and very volatile market for international, long-haul travel. International flights are governed by bilateral agreements between states. These agreements depend on the unstable political relations between states; therefore, part of the airspace is closed at times depending on the relations between countries. In addition, some countries charge royalties for the use of their airspace and often close their airspace completely due to security or other concerns. So, sometimes it is possible to travel to a destination and sometimes it is not.

The reduction in air travel, compared to 2020, means that constraints due to lack of airport and airspace capacity and associated congestion have disappeared.

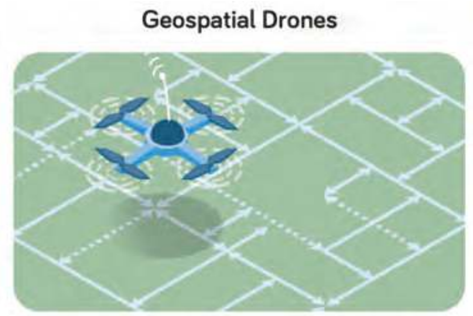
The number of airports has also reduced. The few remaining, large airports are confined to major cities, but there are smaller regional and local airports limited to serving the luxury market. Requirements for air traffic management (ATM) have reduced and aircraft mainly self-separate relying on pilot skills. In the premium market, the pilot is supported by on-board systems derived from the military for situational awareness and collision avoidance. In the lower segment market, separation is maintained by relying completely on pilot skills. There is no monitoring by air traffic controllers.

Flights are planned to avoid adverse weather conditions, which are becoming more and more prevalent because of climate change. Flights are re-planned dynamically during the journey, using continuously updated data, to avoid adverse weather.

There are two main types of aircraft in use, varying by purpose and location; the latter in particular affects the availability of resources and the market potential. The aircraft catering for the luxury market are small, high quality and very fast, reaching supersonic and sometimes hypersonic speeds. The aircraft catering for the mass market are medium or large in size, slower and mainly refurbished. These aircraft are often towards the end of their original design life (thirty- to forty-years old) or rescued from the boneyard by reassembling parts from scrapped aircraft.

The majority of aircraft still use conventional jet engines, except for supersonic flights, but the scarcity of fossil fuels means that the efficiency of these engines has increased. Countries without ready access to oil have developed limited alternative propulsion technologies and alternative fuels although on a small and local scale, principally biofuels from crops or biowaste.

The adoption of urban air mobility (UAM), including flying cars, uncrewed aerial systems (UAS) and drones, has been facilitated by relaxed local certification schemes, although this means that different standards are applied in different places.



In the main, UAM vehicles are a leisurely diversion for the wealthiest part of the population as well as having limited applications as a means of transport. Drones are used for logistics applications, such as parcel delivery, as well as other uses, such as:

- geospatial applications, mapping and surveying;
- monitoring, inspection and management of, for example:
  - utility distribution networks, such as water pipes, oil and gas pipelines and electricity power lines, to detect leaks, defects, damage, threats and hazards;
  - road and rail networks to manage congestion, detect damage to e.g. overhead cables, tracks and road surfaces, as well as threats and hazards, such as vegetation encroachment;
  - remote, offshore, inaccessible and hazardous sites.
- land and sea-use management, including:
  - agriculture, including crop spraying, seed sowing and fertilisation;
  - forestry, including forest fire detection and response;
  - crop monitoring.
- weather and climate monitoring, including:
  - weather observation;
  - frost heave, snow and ice measurement.

In addition, drones and high altitude platform systems (HAPS) are used to support communications, navigation and mapping, surveillance and monitoring, and earth observation. Again, these are offshoots, derived from the military.

The security of flights can be an issue and civil aircraft are fitted with military countermeasures and can, sometimes, be escorted by military aircraft.

Certification is not applied uniformly and products with the same function are approved to different standards depending on where they are designed and manufactured. To speed up certification, physical testing is reduced and transitioned to virtual testing and certification at coupon and system level, but less at full-scale. The associated electronic data are stored for future reference, supporting the development of component identification (ID) approaches, in theory supporting the use of second-hand parts and aircraft.
These data contribute to the development and use of virtual passports or digital twins, which can be used to verify whether a second-hand item is still structurally safe to be reused, or in the case of digital twins, to predict future issues. However, the original equipment manufacturer (OEM) or the government can retain ownership of the data and derived digital tools, potentially limiting the access to those by second-hand users. In addition, in such fragmented world the risk of fraud is very high, therefore the need for secure data systems is paramount.

There has been no focus on sustainability, noise or emissions. However, improved aerodynamics and engine efficiency, to save the already scarce fuel, coupled with reduced traffic means that the overall impact of aviation operations in terms of green-house gas (GHG) and other gases emissions is lower than in 2020. On the other hand, abandoned infrastructure and vehicles and the continued use of raw virgin materials and fossil fuels translate into significant, negative environmental impact.

The research environment

R&D is mainly limited to the national scale with low levels of public funding. This funding is usually subject to restrictive terms and conditions on publication and knowledge-sharing. There is a strong R&D connection between government interests and influence, and industry. There are very few R&D centres of excellence and no international networks. These centres of excellence are appealing places for researchers to work and attract local and international employees. Employment is conditional on stringent and invasive background checks.

In this scenario, there is limited research infrastructure dedicated to specific priority themes, mainly security. In wealthy areas there are specialised wind tunnels needed for supersonic and hypersonic flight. The majority of the research infrastructures are "updates" of older infrastructures, as fragmentation prevents required investment.

The need for industry players to make quick returns on their R&D investments means that innovation is implemented rapidly, aided partly through the removal of institutional and regulatory constraints. This relaxation of regulatory barriers includes the flexibility to trade-off factors such as safety and security.

The majority of research, development and innovation in the Mad Max scenario is driven by military , security and safety requirements to counter a range of threats, including:

- physical threats, such as surface-to-air missiles, both hand-held (MANPADS) and vehicle-launched, air-to-air missiles;
- electronic threats, such as jamming and spoofing of on-board systems;
- health threats, such as naturally occurring pathogens and synthetic biological agents;
- climate threats, caused by increased volatility in weather conditions, including: increased risk of damage caused by high and unpredictable winds, hazardous phenomena such as windshear and microburst, icing, and extremely high temperatures.

Where it is allowed by security classification, military research is spun-off into the civil sector. This spin-off occurs particularly in the security domain covering:

- intelligence-led, dynamic, threat assessment tools to predict, detect, monitor, avoid and counter-act threats;
- physical security, including surveillance and access control, but also protection from climate-related events;
- simulation environment and tools to assess the performance of security concepts and solutions against present and future threats;
- ground-based and on-aircraft counter measures.

There are also other areas of spin-off from military to civil, including:

- highly durable, strong, lightweight, and extreme temperature and pressure-resistant materials, such as ceramic matrix composites and metallic foams;
- additive manufacturing knowledge;
- propulsion systems, including hypersonic and nuclear and related ground test benches for the different type of engines;
- high speed computation and communication networks (wired or wireless).

Key drivers for aeronautical research and innovation

Vehicles

In the Mad Max scenario, there are two main strands of research in the vehicle domain. The first of these focuses on luxury, speed and customisation of new aircraft types and configurations, whereas the second focuses on extending the life of existing air vehicles.

The new aircraft types for the luxurious market are smaller and increasingly have shorter or vertical take-off and landing (STOL, VTOL, STOVL) capabilities, to allow them to access urban areas directly meaning that the boundary between conventional aviation and UAM is blurred in this scenario. For short distances, UAM is a luxurious option and comprises (remotely) piloted, personal mobility solutions.

The small number of long-distance supersonic and hypersonic aircraft use completely innovative airframe configurations, such as transonic blended wing body (BWB), or supersonic civil transport. These aircraft are designed to minimise vibrations, noise and g-forces in the cabin, in such way that acceleration loads from supersonic, hypersonic and suborbital flight are not transferred to the passengers. The vehicle structures use the forces associated with these flight loads, along with friction heating, as a source of energy to boost onboard power supplies, via piezoelectric materials. These high-speed vehicles are constructed from materials able to sustain extreme temperatures, both at structural level and at engine level. These materials include titanium, ultra-high temperature ceramic composites (UHTCC) and metal matrix composites.

New aircraft for the lower quality market segment are still based on traditional design concepts and have very similar appearance to those used in the past, based on a cylindrical fuselage (tube) and wing. However, these aircraft are generally smaller and there have been improvements in aerodynamics through laminar flow technologies both to improve efficiency and fuel-consumption, and in structures, to provide resilience against ever-deteriorating adverse weather conditions, including turbulence, high winds and lightning strikes.

Drones and HAPS are known technologies, spun-off from military applications, across the globe, and are able to fulfil many applications. However, their actual implementation depends on local availability (given the costs involved). These vehicles have high aerodynamic performance with highly agile flight controls and are constructed of high-performance lightweight materials.

For all air vehicles, design is optimised to reduce material use (and thus weight), by structural and topology optimisation. The materials used to construct these aircraft are traditional metal, and thermoset and thermoplastic polymer-based composites. Overall, the properties of these materials are not significantly different from materials used in 2020, but some properties are tailored to improve the passenger experience by reducing noise and absorbing vibration. Thermoset and thermoplastic polymer-based composites can be used at temperatures up to 400°C. The materials used also ensure that aircraft are more resistant to impact. To reduce maintenance, self-healing materials are used, which can reabsorb minor damage, for example from impact of debris and small foreign objects. Self-healing materials are mostly based on smart polymers and nanofillers (nanoparticles, nanofibers, nanowhiskers), resulting in composite systems designed specifically for the requirements of the intended applications. Nanotechnologies are used both for nanocomposites development as well as for the synthesis of the necessary nanofillers.

Intermetallic compounds are used in the design of components which operate at high temperatures. Health monitoring, alerting and other systems are integrated into the structures of all new aircraft – subsonic tube and wing, super/hypersonic and UAM – which are all extremely expensive because of cost and of customisation, resulting in low production volumes. Automation is used to minimise the cost impact of low production runs. Although manufacturing technologies are highly automated, the focus on cost reduction is paramount and control of environmental impacts is neglected. Therefore, secondary products resulting from the manufacturing processes are considered waste, not assets, and are discarded. Gaseous manufacturing by-products are not collected but are released in the atmosphere in uncontrolled manner.

Because new aircraft are very expensive, in less wealthy areas prolonging the life of air vehicles through repeated maintenance, repair and overhaul (MRO) activities is essential. This MRO is basic and inefficient but guarantees a minimum level of safety, concentrating on ensuring that ageing aircraft retain a basic level of airworthiness and safety. In this case, MRO is condition-based and uses whatever tools and spare parts that are available. These, generally, have been passed down through the second-hand market. The information from the part's virtual passport, its digital twin or the structural health monitoring systems associated with it cannot always be exploited, as the data from previous "lives" are not always shared. MRO technologies are mainly long-established ones, adapted or updated depending on the available tools. Limited automated or robotic solutions are used to compensate the lack of specialised human resources. Technology parameter control is often questionable as the second-hand tools are often uncalibrated or have reached the end of their service life.

In wealthier countries, because new aircraft are bespoke, only produced in small numbers and replaced frequently, there is no business case for sophisticated MRO infrastructure and services. Here MRO investment is directed, principally, towards:

- cabin interior improvements;
- updating aircraft with the latest technological “gadgets” and systems;
- increasing (“souping-up”) aircraft performance, as is done with cars and motorbikes.

Here, repair and overhaul are only secondary concerns. The small amount of maintenance and repair that is undertaken is focussed on fixing damage from minor accidents. This approach to MRO is possible because of very lax regulations and it has parallels with military and small aircraft markets, in which vehicles are individually tailored for specific needs of the customers.

Because of being frequently spun-off from the military coupled with risks arising from fragmentation and instability, some technology choices related to the design of the air vehicles and related production are driven by security criteria. Extensive benchmarking of the different competing security solutions and of their impact on the design of the air vehicle is carried out in order to identify the most effective security solution.

Propulsion

The majority of aircraft use conventional, high-bypass turbofan engines optimised for efficiency, not because of environmental impact, but because of the need to extract as much energy as possible from scarce fuels. Advances in the chemical industry have helped to exploit the remaining reserves of fossil fuels, both in the extraction and utilisation phases.

High speed aircraft are optimised for thrust and speed rather than fuel efficiency or noise, using variously turbojet, ramjet, scramjet and, sometimes, rocket engines despite their various negative emissions and noise impacts.

Vehicles for UAM are built on a large variety of propulsion concepts including single rotor helicopters; multicopters; tiltwing aircraft; and jet engines with vectored thrust. In most cases, power is provided by conventional gas turbines. On a small scale in luxury markets, UAM aircraft can be zero emissions or fully electric or hybrid electric, where this is seen as prestigious and fashionable or where oil is in very short supply.

Irrespective of environmentally damaging side effects, in the Mad Max scenario fossil fuels are extracted using the most efficient mechanisms and are supplemented by synthetic jet fuels created using a number of different process, including:

- hydroprocessing esters and fatty acids (HEFA) or hydrotreating vegetable oil (HVO) fuels, using crops such as algae, rapeseed, soya bean, palm and corn;
- Fischer-Tropsch (FT), Fast Pyrolysis (FP), Catalytic Hydrothermolysis (CH), and Hydrothermal Liquefaction (HTL) of agricultural residues to produce drop-in fuels;
- e-fuel power-to-liquid (PTL) processes to produce drop-in fuels;
- synthesis via various processes from waste, including oils and other organic residues;
- extraction from coal using gasification and Fischer-Tropsch synthesis;
- synthesis from ethanol and sugars using ethanol-to-jet and sugar-to-jet processes;
- synthetic biology;
- solar reactors to convert CO_2 into jet fuel;
- hydrogen production using alkaline electrolysis.

Next to synthetic jet fuels and other alternative liquid fuels such as liquified natural gas (LNG), methane and ammonia, nuclear propulsion is also used to power different types of air vehicles.

Systems

As there is a limited production rate for new aircraft, manufacturing is automated as much as possible, to reduce costs, but also to optimise the use of scarce resources and reduce waste (for efficiency not for environmental reasons). This means that virtual practices for design, manufacturing and testing and certification are applied, but not in a harmonised way.

Maintenance is supported by system and structural health monitoring systems, which can detect faults and damage and inform the operator about the necessity for repair and facilitate condition-based maintenance plans. Such systems are oriented towards occasional events (accidental impacts), as usually the service life of the vehicle is much longer than the actual use, because aircraft are replaced frequently in the wealthier parts of the world. In these affluent areas, inspection, maintenance and repair are remote-controlled or automated and supported by sophisticated tools, including drones, smart hangars and 3D printing, with practices spun-off from the military, and supported by the application of artificial intelligence (AI).

In the wealthy parts of the world, the aircraft cabin ensures that the passenger travels in absolute comfort with all of the luxuries of home, including entertainment systems and full and highly reliable, high speed connectivity throughout the flight. Cabin environmental control systems minimise potential passenger irritation and nuisance by minimising turbulence and cancelling noise and vibration, while also protecting passengers against health hazards.

Systems dedicated to security and safety are of extreme importance in this scenario. Cyber security evolves continuously to meet ever changing threats – from foreign powers, terrorists, industrial spies and criminals – in this unstable world. Electronic and software protection against cyberattacks are implemented in aircraft and infrastructure to avoid and prevent sabotage to critical security systems and facilities. The various types of security and safety systems include:

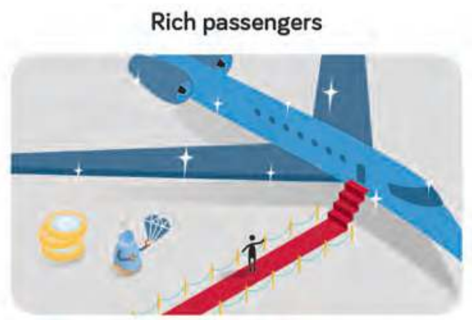
- threat prediction, surveillance, behaviour monitoring, alerting and decision support;
- security response, protection procedures, including the management of multiple attacks;
- passenger security, health and immigration screening based on biometric data;
- flight planning and dynamic replanning, potentially based on AI techniques, using constantly updated situational awareness data, including congestion, weather and security;
- weather prediction, alerting and avoidance tools, for windshear, thunder, fog, sandstorms, and others, fed by big data derived by sensors on each asset, satellites and HAPS. Data are the property of each nation, and are not connected to a global integrated system. These data are used as input to sophisticated atmospheric models that are based on AI and deep learning, resulting in highly accurate weather prediction;
- aircraft on-board systems for applications such as navigation (exploiting multi-constellation GNSS and other navigation sensors), situational awareness, self-separation of traffic, traffic prediction, collision alerting and avoidance, all weather approach and landing, and flight control, during which the single pilot (when present) monitors rather than controls the aircraft. These systems use data collected by the vehicle's own sensors as well as satellite-based and terrestrial navigation, surveillance and weather systems, and use algorithms based on AI techniques, but in this scenario the pilot usually retains control of the aircraft.

Safety and security systems are assessed on their ability to face multiple threats, on their complementarity and on the overall consistency of protection. Appropriate criteria and key performance indicators (KPIs) to assess the quality of safety, security and protection are commonly used, but these vary by location. Benchmarking of different competing secure systems is carried out to identify and choose the most effective solutions. Upgrade of security and safety solutions is made as simple as possible, but easy fixes such as "Plug and Play" solutions are not always possible.

Operational infrastructure

Following the reduction in demand, air transport infrastructure is minimised in the Mad Max scenario. Therefore, the major infrastructure research themes focus on customisation and data processing.

In the main, airports tend to be similar or simpler than in 2020 because the volume of passengers, flights and related traffic control are significantly reduced. All flights are operated point-to-point.



Premium passengers bypass the airport completely. Passengers and their luggage are transported from home to the aircraft with invisible security, health and immigration checks being performed en-route. To ensure data security, encryption is applied based on blockchain technology .

Ordinary passengers follow a traditional path from the airport's entrance to the boarding point. To counter the risk of conflict and terrorism, the airport is a highly secure environment where the passengers and luggage may be subject to stringent and intrusive security, immigration and health checks. However, these checks are fully automated and based on biometric data.

Air traffic management, delivered by air navigation service providers (ANSPs) and other air traffic services (ATS), has all but disappeared. In general, infrastructures such as airport towers and air traffic control centres are not needed anymore, or smaller scale versions are located in proximity of major airports. The major part of the infrastructure is used to collect data for weather prediction and to alert aircraft about possible threats as well as to support aircraft navigation and communications. This infrastructure is supplemented by satellite systems and HAPS.

Automation and low levels of traffic mean that aircraft can fly freely, without regulations, in the entire airspace, navigating and avoiding collisions using on-board systems and pilot judgement. Ground operations are also decreased following the reduced number of passengers, and all services are still based on ground vehicles that are fuel based and operated by ground personnel.

Summary

The research drivers for each dimension – vehicle, propulsion, systems and infrastructure – are summarised in the following table for the Mad Max scenario.

Dimension	Research drivers

Aircraft
• tube and wing
• BWB
• supersonic
• hypersonic
• suborbital
• Drones
• HAPS
	Aerodynamics
	• drag reduction
	• supersonic and hypersonic capability
	
	Structure
	• resilience against adverse weather
	• integrated structural health monitoring
	
	Materials
	• noise, vibration and g-force reduction
	• friction heating as an energy source
	• (ultra) high temperature materials
	• lightweight materials
	• self-healing
	    • smart polymers
	    • nanofillers
	• nanocomposites
	• high impact resistance
	
	Design
	• structural and topology optimisation

Propulsion	Engines
	• high by-pass turbofan efficiency optimisation
	• supersonic and hypersonic capability
	    • turbojet
	    • ramjet
	    • scramjet
	    • rocket
	• hybrid electric
	
	Energy
	• traditional and synthetic jet fuels
	• batteries
	• alternative liquid fuels (LNG, methane)
	• nuclear power

Dimension	Research drivers
Systems	Virtual design, manufacturing, test and certification • virtual passports • digital twins Maintenance • structural health monitoring and alerting • automated inspection, maintenance and repair • smart hangars • 3D printing Cabin environment optimisation • personal entertainment • continuous high-speed connectivity • vibration control • noise cancelling Security • threat prediction • surveillance • behaviour monitoring and alerting • decision support • cyber security • encryption, blockchain Passenger information Passenger screening (security, health and immigration) • biometrics • automation Four-dimensional flight planning and dynamic replanning • situational awareness • automation • artificial intelligence, machine and deep learning Weather prediction, alerting and avoidance • improved atmospheric models • artificial intelligence, machine and deep learning

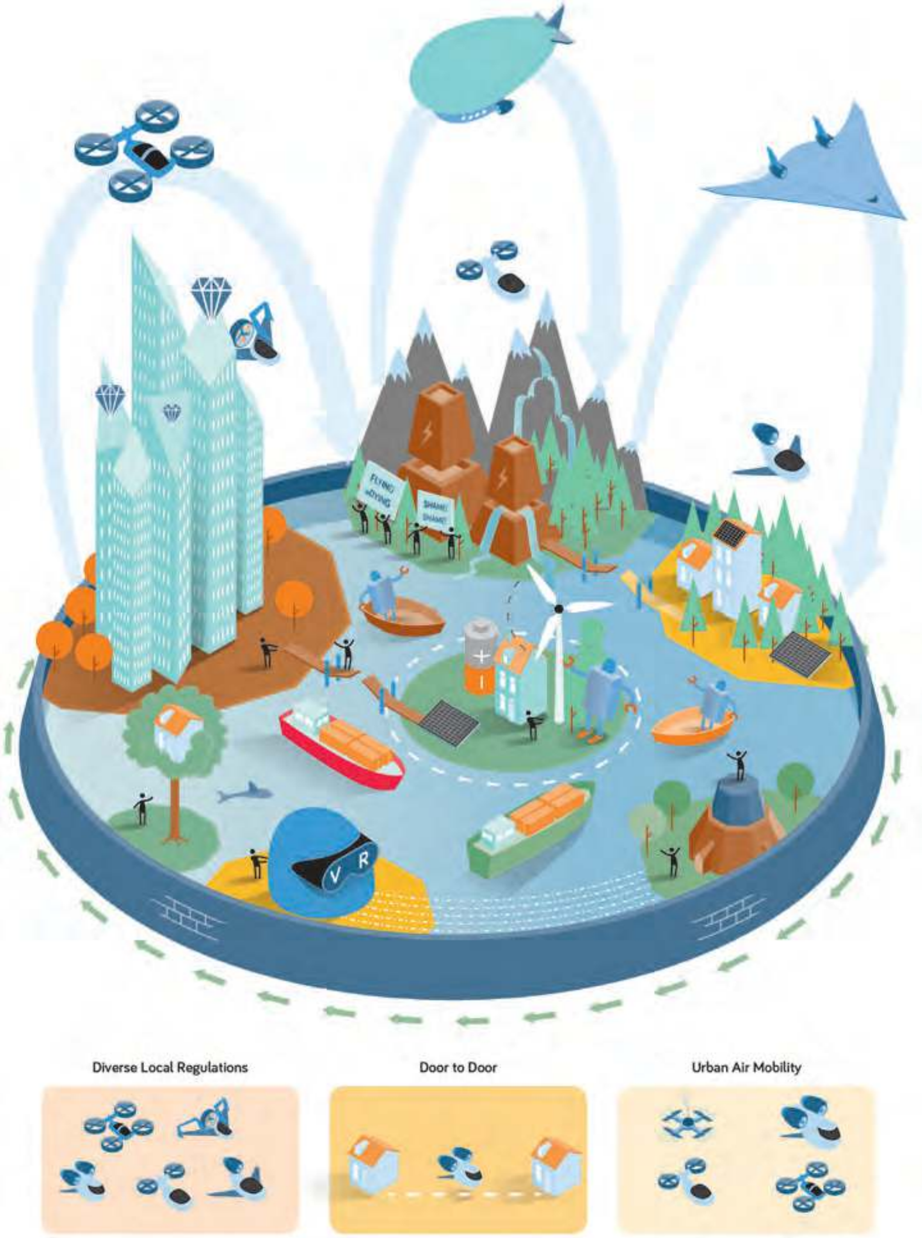
Dimension	Research drivers
Systems (continue)	Aircraft on-board automation • navigation • situational awareness • self-separation, collision avoidance and alerting • flight control • decision support • artificial intelligence, machine and deep learning
Operational infrastructure	Communications, navigation, surveillance and monitoring system with terrestrial, satellite and HAPS

Scenario 2: Tech for You

...aviation: side by side with alternative technology in islands of choice, competition, and customisation

A world organised as numerous discrete islands, of variable size, characterised by multipolarity and competition between them; high-cost, low economy-of-scale production offset by widespread automation; market driven by consumer choice and desires; free market economies; high R&D with national and short-term focus; different approaches to and meaning of sustainability in different islands.

Mobility is flexible with air transport part of the local, intermodal transport system. The overall approach is to strive for door-to-door mobility.



How we fly in this scenario

In the Tech for You scenario, aviation is one element of the overarching mobility as a service (MaaS) concept, at the complete disposal and meeting all of the needs of the customer.

Within each island, journeys are seamless across different modes – sea, land and air – for everyone, enabled principally by the societal acceptance of autonomous vehicles in all modes. Transport modes available for use vary depending on the geographical location. Aircraft in different configurations, high-speed rail, ships and hyperloop are available for long distance journeys. Intra-island, the full range of UAM solutions is available for ultra-short to short-range, door-to-door mobility. However, despite the variety of solutions, due to global political fragmentation, the solutions implemented in different islands are not necessarily the same and, in the extreme, can be incompatible between islands.

The impact of this fragmentation on air transport is that inter-island connectivity is governed by bilateral agreements or, in the most optimistic situation, cluster agreements. These agreements cater for the different regulations that are applied in different places. This means that the agreements can specify constraints on technologies, aircraft types, propulsion, fuels and aircraft characteristics, such as noise footprint and full life-cycle environmental impact, depending on the parties involved. Different requirements may be in place at different times and vary at short notice.

To guarantee connections, digitalisation, the use of information and communications technology (ICT) and virtual technologies for both business and leisure purposes, has increased and improved, offering a real alternative to all types of travel. Combined with increased societal awareness about the negative impact on the environment, travelling in general is not always an option nor is it always desired.

The combination of all these factors has caused the demand for international air travel to decrease in volume and increase in cost. Long-haul journeys have also become less convenient because of global fragmentation and instability, which increases the risk of exposure to threats of different kinds. Therefore, demand for flights is dominated by short journeys, performed using UAM solutions.

In response to the plethora of alternatives to travel, the aviation industry has been stimulated to become incredibly competitive and customer-focused.

Customers have access to many options and digital tools to enable them to design their personalised journey and reconfigure en-route if needed, to provide complete door-to-door mobility solutions, within islands and sometimes at inter-island and worldwide level. Tools and apps enable the passenger to make choices depending on personal preference, which include but not be limited to price, journey time, convenience and sustainability. Luxury journeys can be selected or, at the other end of the spectrum, no-frills journeys are available to passengers who want a more basic service or accept intermediate stops. Many other options are also provided, including ultra-healthy trips; "old-time" experiences using vintage aircraft and traditional service; highly sustainable travel; adventure rides using very fast jets; family options; no-children options; and so on.

Planning and management of air traffic is integrated into local systems and processes for management of MaaS to enable multitudes of door-to-door, personal journeys and connections with long-distance transport. Planning systems take passenger history and preference into account and use intelligence available from historical, real-time and forecast systems, aided by big data technologies, highly accurate weather models and individually optimised 4D trajectories. The multitude of planned flights is then optimised at local and island network level. Interfaces exist between island systems to facilitate longer journeys.

Airspace has been restructured within each island to cater for the shift of demand and change of aircraft mix in the sky. At low altitudes, local airspace can be very congested especially around urban areas, which are crowded with a very heterogenous mix of traffic including a range of UAM vehicles and some conventional, longer range aircraft. At higher altitudes and on international routes there is much less traffic and lower congestion than in 2020. To facilitate navigation in the air traffic system and to support maintenance and other tasks, a high number of specialised sensors are integrated into vehicle structures.

Depending on location, there is very limited public tolerance of noise and pollution from aircraft. There is also public concern about visual disturbance, especially in urban areas, caused by very dense concentrations of UAM vehicles operating at low altitudes. Furthermore, in some areas there are disputes about the ownership of airspace at low levels above privately-owned property. These issues are addressed in different ways depending on the specific island. In general, though, all vehicles are designed, built, operated and maintained for flexibility, and the airspace is organised to allay public concerns on environmental and social impact.

The varied character of each island and the desire for customisation means that diverse aircraft types, classes of travel and connected services are developed based on the needs of the local market, cultural preferences and available national resources. Air vehicles come in all sizes, from small, ultra-short-range flying cars and taxis for UAM through to large aircraft for long-haul international travel. Various energy sources for the propulsion systems are used, from conventional fossil fuels to sustainable alternative fuels (SAFs), from solar to hydrogen. Lighter-than-air vehicles – airships – are used for long distance non-urgent freight, and also as “cruise-like” leisure flights.

Airplanes used for longer range flights that have a flight crew on-board are usually operated by a single pilot supported by automated systems and decision support tools in the cockpit. Short range aircraft used for passenger UAM are fully autonomous.

Remotely piloted and autonomous drones are used for logistics applications, such as parcel delivery, as well as many other uses, such as:

- geospatial applications, mapping and surveying;
- monitoring, inspection and management of, for example:
    - utility distribution networks, such as water pipes, oil and gas pipelines and electricity power lines, to detect leaks, defects, damage, threats and hazards;
    - road and rail networks to manage congestion, detect damage to e.g. overhead cables, tracks and road surfaces, as well as threats and hazards, such as vegetation encroachment;
    - remote, offshore, inaccessible and hazardous sites.
- land and sea-use management, including:
    - agriculture, including crop spraying, seed sowing and fertilisation;
    - forestry, including forest fire detection and response;
    - fisheries monitoring and protection;
    - monitoring environmentally sensitive areas;
    - crop monitoring;
    - public right-of-way assurance.
- humanitarian aid and disaster response, covering, for example:
    - search and rescue;
    - assessing damage from natural disasters;
    - medical aid and food distribution.
- weather and climate monitoring, including:
    - weather observation;
    - frost heave, snow and ice measurement.
- conservation in game reserves and the wilderness:
    - anti-poaching surveillance and enforcement;
    - human access and activity control;
    - animal tracking;
    - biodiversity assessment.

In addition, drones and HAPS are used to support communications, navigation and mapping, surveillance and monitoring, and earth observation.

The fragmentation into islands has resulted in a lack of global standardisation, causing the need for multiple certifications for aircraft and equipment that meet multiple, different environmental, safety and security requirements.

Physical testing is still being performed, but, depending on the island and the specific infrastructure available, it is sometimes reduced and transitioned to virtual testing and qualification, and digital twin approaches (experimental/ digital, hybrid tests), which can be more efficient than physical testing and give sufficiently reliable results. Where physical testing still occurs, the associated electronic data are stored for future reference, supporting the development of component identification. However, there can be restrictions on the sharing of those data caused either by the fragmentation that is a characteristic of this scenario or because the original equipment manufacturers (OEMs) want to control access for commercial reasons.

The research environment

R&D and innovation are well-funded within the Tech for You islands. The character of R&D is both highly proactive to propose new services and products and, at the same time, reactive to real or perceived problems. R&D is characterised by competition, parallel developments and duplication, as it is repeated in different places without any frameworks for cooperation. Despite the lack of these frameworks, researchers strive to collaborate internationally and there are some large-scale research programs, mainly related to sustainability. Involvement of customers in R&D activities, as part of co-creation or concurrent design approaches, is limited, as the abundance of demand makes the involvement of the end-user unnecessary.

The need for quick returns on R&D investment, fuelled by the need to react quickly to demand for customised solutions and to maintain competitive advantage, means that there is a short R&D cycle that rapidly delivers high technology readiness level (TRL) results. On the other hand, the possible return to investment in case of brand new disruptive innovative products is attractive for researchers, who are free to explore unchartered research dimensions.

Despite the short development-to-market time, safety and security considerations are carefully evaluated supported by research in a number of areas, including:

- intelligence-led, dynamic threat assessment tools to predict, detect, monitor, avoid and counter-act threats;
- physical security, including surveillance and access control;
- a security simulation environment and tools and assess the performance of security concepts and solutions against present and future threats;
- ground-based and on-aircraft counter measures against a wide range of threats: including physical threats, such as surface-to-air missiles, both hand-held (MANPADS) and vehicle-launched, air-to-air missiles; electronic threats, such as jamming and spoofing of on-board systems; and health threats, such as naturally occurring pathogens and synthetic biological agents.

The limited international cooperation that exists is oriented into exchanging solutions to common or similar challenges. Products or solutions developed in particular circumstances, which can be implemented elsewhere with only minor changes, are welcome but not actively sought. Joint collaboration to solve common issues is difficult, due to different funding sources with limited access and irregular opportunities to exchange information (related to borders being open or closed, for example).

R&D is underpinned by locally standardised, optimised tools and engineering processes. All these applications are fully digitalised. Extensive use of automation, real time computing, data fusion, and other ICT solutions support short term predictions and decision making, alerting, and monitoring functions. To support digitalisation, high speed computation and communication networks (wired or wireless) are available at low cost. Despite full digitalisation, sharing of research methods, the associated data and models, and outcomes is restricted given the high competition between companies and islands. Intellectual property is controlled, and if shared, is more easily shared within the islands' border than with other islands .

Each island provides the full range of R&D capabilities needed to support development of solutions to its own priorities from very low to the top TRLs and through to transition into service, including testing and certification. Though this simplifies developments and allows multiple concurrent test campaigns, it also means that there is duplication and inefficient use of facilities. In this scenario, based on a wide panoply of technology offers and needs, research infrastructure plays a key role for test and deployment from individual technologies through to systems-of-systems. Ground test benches for the different type of airframes, engines and systems (electric motors, electric and electronic networks, fuel distribution, etc.) are used in order to ensure the required level of safety and security.

Fast prototyping, and local digital and virtual certification processes support R&D, by enabling the development of flexible and adaptable solutions prior to commercialization. This flexibility includes the ability to trade-off between parameters such as safety, security and cost.

The widespread application of UAM and the fast R&D cycle mean that drones and UAM vehicles are the ideal, real-life, platform to implement innovations and to assess their impact, especially with regard to the integration of UAM into the urban setting, and its impact on infrastructure needs for refuelling, recharging, maintenance and passenger operations.

Key drivers for aeronautical research and innovation

Vehicles

In the Tech for You scenario, research in the vehicle domain is driven by the need for customisation and efficiency.

Aircraft for long- and ultra-long range missions have become smaller and in the largest part, cylindrical fuselages (tube and wing) designs have been replaced by novel configurations, such as BWB, especially in combination with alternative energy sources to fossil fuels or SAFs. These airplanes are operationally agile, reconfigurable and modular to be flexible to volatile demand and different requirements in different places. This flexibility includes the capability to change size by adding or taking away cabin modules from a particular design throughout the life-cycle; the ability to change engine type for different journeys if needed; and interchangeable interiors. Aircraft used for short and medium-range missions are also smaller and increasingly have short or vertical take-off and landing (STOL, VTOL, STOVL) capabilities, to allow them to access urban areas directly. To an even greater extent than for the long and medium distance airplanes, UAM vehicles are designed specifically for customisation.

Aircraft cabins are customisable, in terms of look, feel and facilities, to address passenger desires but with the common theme of minimising all types of vibration, noise, electromagnetic interference and turbulence. Motion and noise cancelling systems are used to avoid air sickness and to improve passenger comfort, especially in UAM. The passenger can travel in absolute comfort with all of the luxuries of home, including entertainment systems, based on virtual and augmented reality with full and highly reliable, high speed connectivity throughout the journey. Depending on the type of journey that the passenger has selected, there may be cabin crew or robots on-board to emphasise the customer experience. Psychoacoustics analysis, supported also by specific testing, supports configuration optimisation with respect to noise.

To manufacture such customised air vehicles, different design and manufacturing approaches are used in different places, ranging from traditional methods through to AI-aided generative design with structural or topological optimisation, in some areas venturing into biomimicry. The end-to-end process from design to manufacturing is fully automated and optimised for low production runs. Large-scale use is made of additive manufacturing, sometimes to produce whole aircraft.

Vehicles are built of lightweight materials, including sustainable and recycled materials, but also virgin and expensive smart materials. In most places, materials used to construct these aircraft are traditional metal, and thermoset and thermoplastic polymer-based composites but they are lighter and stronger than in 2020, with properties tailored to improve the passenger experience by reducing noise and absorbing vibration caused by more agile movements.

Materials have been engineered and selected for longevity; they have high impact resistance, excellent protection from environmental agents and are self-healing. Self-healing materials are mostly based on smart polymers and nanofillers (nanoparticles, nanofibers, nanowhiskers), resulting in composite systems designed specifically for the requirements of the intended applications. Nanotechnologies are used both for nanocomposites development as well as for the synthesis of the necessary nanofillers. In some islands, waste products and residues must be kept to a minimum. Many of the chemical by-products (gaseous, liquid, solid) from the manufacturing process are utilised in other technological processes, to fulfil environmental regulations where these are in place.

In 2050 thermoset and thermoplastic polymer-based composites can be used at temperatures up to 400°C and low to -250°C. Thermoplastic matrix composites are fully implemented and far exceed thermoset matrix composites rate in the aircraft components, due to their high recyclability capabilities. The manufacturing processes for thermoplastic composites are fully controlled, using in-situ sensors for monitoring and live-recording across the entire process. This results in minimal material loss and process scrap, and a very low level of product errors. Processing of polymeric composites is controlled at the chemical structural level with the aid of spectroscopic and/or microscopic techniques tracking the evolution of chemical reactions (chemical bond formation, reaction yields, polymerization rate, etc.).

These materials have the capability to include integrated sensors for structural health monitoring and to facilitate customised MRO schemes. In places where sustainability is very high priority, vehicles (particularly small vehicles) are constructed from bio-based and other sustainable materials: wood, composites with biodegradable resins, and natural fibres, such as wood, bamboo, hemp, flax, basalt and glass.

To enable additional product functionality, smart materials and functionally graded materials are implemented on demand. Due to difficulties in reuse or recycling, these materials are not allowed where stringent environmental regulations are in place.

Operational cost is a one of the key drivers; this means aircraft are designed to be extremely aerodynamically efficient. Aerodynamic efficiency is supported by the ability of the aircraft to change shape via morphing flying surfaces and, in some case, to have flapping wings. In some places, vehicles incorporate cloaking capabilities and noise cancelling technology to reduce visual and noise disturbance from high density UAM operations.

MRO is based on bespoke processes and technology that vary from place-to-place and vehicle-to-vehicle. However, in general maintenance is predictive and is supported by real-time system and structural health monitoring using sensors integrated within the vehicle. Some vehicles are modular, with easily interchangeable and re-usable building blocks but other vehicles are not and are built as a single, indivisible unit. Inspection, maintenance and repair are remote-controlled or automated and supported by sophisticated tools and techniques, including AI, drones, smart hangars and 3D printing for on-site manufacturing of spare parts. Overhaul is mainly focused on additional customisation to ensure that the vehicle remains up-to-date against ever-evolving customer demands and fashion.

Digital twins combine design, manufacturing and use information to determine the condition of the structure or component to predict the need to repair or retire the component, trading off between the impacts of repair, reuse and end-of-life.

In some places, vehicles and their components are recycled or, in the case of modular design, reused, in a fully circular process.

Because of competition between islands, some technology choices related to the design of the air vehicles and related production are driven by security criteria. Despite the wide variety of aircraft types, the need and consistency of different security solutions used is assured by benchmarking different competing technological evolutions in order to identify and choose the most effective solution in terms of security and its impact on airframe choices.

Propulsion

Aircraft propulsion ranges from technologies that have zero environmental impact through to the use of conventional fossil fuels depending on local policies. However, because of the need to be compatible with multiple policies, fossil fuels are almost never used for international flights, which use very efficient jet engines powered by SAFs. Synthetic hydro-carbo based SAFs are produced using a variety of processes, including:

- hydroprocessing esters and fatty acids (HEFA) or hydrotreating vegetable oil (HVO) fuels, using crops such as algae, rapeseed, soya bean, palm and corn;
- Fischer-Tropsch (FT), Fast Pyrolysis (FP), Catalytic Hydrothermolysis (CH), and Hydrothermal Liquefaction (HTL) of agricultural residues to produce drop-in fuels;
- e-fuel power-to-liquid (PTL) processes to produce drop-in fuels;
- synthesis via various processes from waste, including oils and other organic residues;
- synthesis from ethanol and sugars using ethanol-to-jet and sugar-to-jet processes;
- synthetic biology;
- solar reactors to convert CO_2 into jet fuel.

Other alternative liquid fuels include liquified natural gas (LNG), methane, and ammonia, produced using dedicated processes. Hydrogen, produced using alkaline electrolysis or other sustainable techniques, is also used. Nuclear power has limited applications in islands that lack other resources. Solar power is limited to long distance and slow flights.

For short- and medium-range flights, propulsion systems are based on widespread electrification with different degrees of hybridization, including zero emissions hybrids. Electrification is enabled by high capacity batteries or fuel cells.

Short-range aircraft come in a variety of forms, including conventional single rotor helicopters; multicopters; tiltwing aircraft; and aircraft with vectored thrust. All UAM vehicles are fully electric. In the case of rotorcraft, all aspects of aerodynamics, mechanical and acoustics design for distributed electric propulsion (DEP) propellors, including nacelle installation, is focused on noise minimisation. Psychoacoustics analysis, supported also by specific testing, supports configuration optimisation with respect to noise.

Systems

The systems enabling aviation in the Tech for You scenario are focused on managing the high volume of UAM traffic and related security and safety issues. Dedicated systems provide the capability for formation flying with master and slave aircraft, and climate optimised routing, when required.

In this scenario routes are allocated based on airspace optimisation. Each flight is assigned a dedicated 4D trajectory, with boundaries of manoeuvre (tunnels in the sky). The trajectory can be modified in real-time, to accommodate for any changes that occur.

In the Tech for You islands, the systems dedicated to security have been identified based on their efficiency to face multiple threats, on their complementarity and on the overall consistency of protection. Appropriate criteria and KPIs to assess the quality of security and protection are commonly used. These KPIs are consistent with the wide variety of mobility solutions. Benchmarking of the different competing secure systems is carried out in order to identify and choose the most effective security solutions. Upgrade of security solutions is as easy as possible, mainly via Plug and Play solutions. System-level certification is critical and constantly changing to enable the implementation of new solutions.

Urban Air Systems

Security systems include:

- security threat prediction, surveillance, behaviour monitoring, alerting and decision support, covering, for example, crime, terrorism and pandemic;
- risk-based assessments;
- security response, protection procedures, including the management of multiple attacks.

The main areas where systems are applied in the Tech for You scenario include:

- planning, managing and operating the local multimodal transport infrastructure;
- planning, managing and optimising thousands of concurrent, customised local door-to-door journeys based on traveller preferences, including climate optimised routes where required;
- system and structural health monitoring, alerting systems and other systems integrated into the vehicle structure to predict and detect faults and damage and facilitate predictive and condition-based maintenance;
- weather prediction and alerting tools at micro, meso and macro scales ranging from prediction of wind flows around buildings for safe UAM, through wind shear, thunder, fog and sandstorm events, to jet stream and high altitude winds. Real-time and historical data are provided by crowd-sourcing from vehicles themselves, local sensors, satellites and HAPS and are processed using algorithms based on AI, machine and deep learning;
- aircraft on-board systems for applications such as 4D navigation and related autonomous integrity (exploiting multi-constellation GNSS and other navigation sensors), situational awareness, self-separation of traffic, traffic prediction, collision alerting and avoidance, all weather approach and landing, and automatic flight control. For crewed aircraft, operating long flights, systems monitor crew workload and provide decision support whereas for short, UAM flights, systems are mainly fully autonomous. These systems collect, integrate and fuse data collected by the vehicle's own sensors as well as satellite-based and terrestrial navigation, surveillance and weather systems;
- controlling and optimising the cabin environment using intelligent systems, including vibration, motion and noise cancelling, inflight entertainment using virtual and augmented reality and immersive technologies, automated cabin service and projection of real-time outside views instead of windows. Cabin systems also cater for the provision of reliable high-speed connectivity;
- passenger security, health and immigration screening based on biometric data;
- passenger information and advisory systems, including:
- gathering and provision of urban intelligence for customised journey planning and optimisation;
- personalisation of services to individual passengers, including transport mode choices optimised according to passenger defined criteria;
- automatic reconfiguration of journeys in the case of disruption.
- systems for the integration and management of both electric and thermal engines using alternative fuels. Factors that need to be addressed include the electric network, electronic controls, thermal and power management, hydrogen tank integration, and others. All propulsion systems require power train integration, in particular the interfaces with the main engine and subsystems; for example, electric motors with mega-Watt level power supplies need specific system and material technologies, e.g. superconducting stators and rotors;
- energy management systems for integrating the different high performance solutions in different types of aircraft. An integrated and smart thermal and power management (ITPM) system, supported by AI and applied all along the electric network, is required for managing complex architectures. There is a constant need for R&D in the field of:
  - aerodynamic improvements that require secondary on-board power: morphing wings, load alleviation, active flow control;
  - drive trains with potential for tail cone thruster (TCT), counter-rotating open rotors (CROR), hybrid electric propulsion (HEP), DEP, and boundary layer ingestion (BLI) propulsion options;
  - multiple distributed heat sources (gas turbine, power electronics, batteries, fuel cells, electric drives, power generation modules, battery management system,

cables and buses);
- changes in heat sinks (potentially less fuel or liquid hydrogen as coolant, composite aircraft skin working as a thermal conserver, need for integrated air intakes, cooling issues inferred by platform or low-altitude operations like queuing times before take-off and landing);
- prioritizing power assignment to vital functions (power management, failure mode analysis, etc.).

Specifically for UAM, another area of system research relates to trade-off between on-board computing and terrestrial computing, considering:
- terrestrial high performance computing data centres optimised for sustainability and circularity;
- contingency needs for autonomy to enable the vehicle to continue to fly safely (onwards to the destination or divert to the nearest vertiport) if connections are lost to GNSS or to any other network (e.g. 5G-6G-7G-8G);
- the cost of the on-board computing capacity;
- the available bandwidth on the networks used.

Most data processing and computing are done in terrestrial island-level information centres. These centres provide information (e.g. weather, traffic prediction, safety and security predictions, pollution and noise) to all vehicles flying within their coverage area. On-board computing concentrates on autonomous flying, refining local and short-term and contingency aspects.

Other systems that underpin this scenario are based on high performance computing, AI, machine learning and deep learning supported by the large-scale collection, integration and synthesis of data. Cyber security evolves continuously to meet ever changing threats. In general, highly trusted automated systems have resulted in a change of balance of the responsibility for decision-making from human to machine, with the human playing more of a monitoring role, but with the capability to over-rule the machine if needed. These systems are particularly relevant in design, manufacturing and MRO, which are all highly automated, based on AI learning and robotics applications.

Operational infrastructure

Much of the infrastructure that supports flight has become integrated into the urban landscape, which has been re-designed to include and exploit the third dimension. Multimodal interchange nodes are at the core of the sustainable architecture for mobility in the integrated transport infrastructure, providing MaaS, together with railway tracks, hyperloop and parking facilities. Where needed, specific infrastructure to support air operations is provided, including runways, vertiports, charging stations for UAM and facilities for the distribution and use of alternative fuels.

Interchange nodes are indivisible from the built environment, containing offices, shopping centres, leisure facilities, hospitality centres and art galleries. A few dedicated airports remain to support international flights and are located outside of cities. These are reconfigured to cater for seamless transfer between aircraft, connecting land transport and UAM. For long journeys with an air segment, the passenger travels from home, using convenient land transport or a UAM solution to the nearest airport where transfer to the aircraft occurs. Invisible security, health and immigration checks are performed either at home or en-route to the airport or aircraft.

Networks of sensors collect data on the transport system and the environment including pollution, contrails, noise, visual disturbance, weather, vehicle status, congestion, health, and safety and security threats. These monitoring networks comprise terrestrial systems, HAPS, space-based systems and vehicles themselves. The data collected are fed into global information centres that analyse and synthesise the inputs to produce and publish status reports (nowcasts) and short-, medium- and long-term forecasts. The data are also used to train neural network, AI and quantum computing algorithms. In some places, where sustainability is a priority, the data collected are used in atmospheric models to understand and minimise climate impact. The data also feed into the aircraft navigation systems, so that climate-sensitive parts of the atmosphere can be avoided.

Air traffic management, provided from airport towers and air traffic control centres, has all but disappeared, with the only remnants providing connectivity for long distance flights between different islands. Even then, ATM is automated and there is no monitoring by air traffic controllers. More often, outside of dense airspace, aircraft mainly self-separate autonomously using on-board systems situational awareness and collision avoidance systems.

At low altitudes, especially around urban areas, U-space is fully automated and configured to cater for and ensure the safety of the very dense, congested, complex, asymmetrical and heterogeneous mix of vehicles, including aircraft transiting to and from higher flight levels as well as a huge variety of remotely-piloted and autonomous drones and other UAM vehicles.

Initially, U-space management optimises strategic and tactical plans to ensure safety, security and efficiency of UAM traffic. After that, automation and low levels of conventional traffic mean that aircraft can fly freely in all airspace, navigating and avoiding collisions using on-board systems. These operations include single aircraft but also master and slave formation flying for long distance flights. To support operations and provide an overall situational picture, U-space management collects data from, and communicates through, a network of sensors, including terrestrial monitors, HAPS and satellites as well as the air vehicles themselves, arranged as a flying ad-hoc network (FANET). In addition, HAPS are used to support navigation and mapping, surveillance and monitoring, and earth observation. In some places, tethered air vehicles are used to generate airborne wind energy by exploiting wind and air movements.

Summary

The research drivers for each dimension – vehicle, propulsion, systems and infrastructure – are summarised in the following table for the Tech for You scenario.

Dimension	Research themes
Aircraft	Aerodynamics
• tube and wing	• drag reduction
• BWB	• shape-changing/morphing flying surfaces
• master and slave	• flapping wings
• UAM	
• Drones	Structure
• HAPS	• integrated structural health monitoring
	• integrated sensors for U-space management
	• cloaking to reduce visual impact
	Materials
	• noise, vibration and motion cancelling
	• lightweight materials
	• self-healing
	• smart polymers
	• nanofillers
	• nanocomposites
	• high impact and extreme temperatures resistance
	• thermoplastic matrix composites
	• bio-based and other sustainable materials
	• smart materials
	• functionally graded materials
	Fully automated integrated process from design to production
	• virtual testing, certification and qualification
	• digital twins
	Design
	• AI-aided generative design
	• structural and topology optimisation
	• modularity
	• master and slave formation flying
	• biomimicry
	Production
	• automation
	• additive manufacturing

Dimension	Research themes
Propulsion	Architectures • distributed electric propulsion (DEP) Engines • high by-pass turbofan efficiency optimisation • zero emissions hybrid electric • fully electric Energy • synthetic jet fuels • alternative liquid fuels (LNG, methane. ammonia) • batteries • fuel cells • hydrogen • solar power
Systems	Virtual design, manufacturing, test and certification • virtual passports • digital twins Maintenance • system and structural health monitoring and alerting • automated inspection, maintenance and repair • smart hangars • 3D printing Cabin environment optimisation • personal entertainment • continuous high-speed connectivity • motion and vibration control • noise cancelling • cabin service robots Security • threat prediction • surveillance • behaviour monitoring and alerting • decision support • encryption, blockchain

Dimension	Research themes
Systems (continue)	Passenger information Passenger screening (security, health and immigration) • biometrics • automation Planning, managing and operating the integrated, island-level, multimodal transport infrastructure Door-to-door journey planning, management and optimisation • journey customisation Weather prediction, alerting and avoidance • macro, meso and micro models Aircraft on-board automation • 4D navigation • master and slave formation flying • situational awareness • self-separation, collision avoidance and alerting • flight control • decision support for crewed flights (long distance) • full autonomy for UAM Aircraft energy management and control systems • integrated and smart thermal and power management (ITPM) UAM • trade-off between on-board and terrestrial computing • contingency/resilience for system failures U-space management • automation • autonomy

Dimension	Research themes
Systems (continue)	Supporting capabilities • High performance computing • High speed connectivity • Big data • AI, machine learning and deep learning • Robotics • Cyber security • Plug and play solutions
Operational infrastructure	Fully autonomous, local U-space management system Integrated multi-modal transport system • multimodal interchange nodes • door-to-door ticketing Communications, navigation, surveillance and monitoring system with terrestrial, satellite and flying components (vehicles and HAPS)

Scenario 3: Stripping Down

...aviation: sustainability achieved in a stable, coordinated and harmonised world

A world characterised by political stability; a few continental-sized democratic blocs; global harmonisation between blocs; limited consumer choice; markets organised around incentive-based regulation; planned, slow but stable economic growth; prioritised and government-directed sustainability.

Sustainable intermodal generic solutions adopted to reduce environmental impact and achieve sustainability policy objectives. There is limited and highly controlled mobility due to sustainability objectives and incentives.

How we fly in this scenario

In the Stripping Down scenario, aviation is part of a multimodal transportation system optimised to achieve zero-emission status at global level.

In this politically stable world, travel is governed by a global legal framework defined through universally agreed mandatory standards on sustainability based on the three United Nations (UN) sustainable development pillars to reconcile environmental, social and economic demands, including safety, security, and health. Borders are open but travelling is allowed only for government-authorised, zero climate-impact, journeys. International travel requires health, security and immigration checks, which are organised to be minimally intrusive and are based on citizen databases that are shared between governments. International flights are only allowed if certain minimum requirements are met, for example thresholds are set on minimum actual load factors below which the flight cannot go ahead. This means that flights can be unreliable, and subject to cancellation at short notice.

Available and approved transport modes include emission-free aircraft, high-speed rail and hyperloop, and at the local level, electric buses, bicycles and scooters and a limited range of UAM solutions, all in a shared economy context. Government regulation directs the traveller to select a specific combination of modes for their journey, principally based on sustainability, rather than providing or allowing personal choice. Public transport is strongly encouraged over the use of private vehicles. Flying is only allowed when it is the most sustainable or only mode available.

Governmental control is built upon and supported by a general social aversion to travelling, purely based on its past unsustainable character and its impact on the environment. There is absolutely zero tolerance to the pollution, and to noise and visual disturbance generated by transport. All transport modes are treated equally in this respect. A set of KPIs and standardised global climate impact models are used to monitor continuously the impact of transport against the UN Sustainable Development Goals (SDGs). There are incentives to exceed sustainability targets. Conversely, there are penalties, such as fines, for failure to meet the targets.

The combination of strict regulation, taxation on transport's full external (pollution, noise, visual disturbance and other negative social impacts) cost, unreliability in the service, and public reluctance to fly means that aviation demand is very low and is restricted to low frequency, long-haul journeys and essential flights. There are very few airlines, consolidated to, typically, one per continent, from the multitude of airlines operating in 2020.

Reduction in demand means that there is no airspace congestion and that capacity is not a constraint either in the air or at airports. Flights occur from large airports located near to mega-cities with journeys to the airport being made by the most appropriate transport mode. The journey is not configured to the passenger's comfort or convenience, but optimised for the lowest negative environmental impact. The distance from home to the nearest or most suitable airport might be long.
Multiple connecting flights and long layovers at intermediate airports might be needed between the origin and destination airports.

All flights are planned, to climate optimised 4D trajectories, using predictive algorithms to eliminate adverse environmental and social impact, such as emissions, noise and visual disturbance. When en-route, flights are re-planned dynamically, using continuously updated data, to maintain climate optimised trajectories and to avoid threats, such as adverse weather.

Due to low volumes of traffic, ATM is standardised globally and fully automated without the need for air traffic controllers. ATM is used as a regulatory tool to ensure that flights adhere strictly to rules, including conformance with airport and airspace slots and other criteria, such as achieved load factors.

Aircraft that are used for long flights have crews on-board but are usually operated by a single pilot supported by remote automated systems and decision support tools in the cockpit. Automated on-board systems are used to ensure separation between all air vehicles.

Sustainability considerations mean that the use of fossil fuels is completely prohibited, for any application. Aircraft are fully sustainable. Noise and other negative social impacts, such as visual disturbance, have been eliminated. Aviation's environmental impact is assessed on a cradle-to-cradle basis. The assessment considers the entire impact of the vehicle, its systems and energy source, including energy production and storage mechanisms, not only direct emissions from the aircraft. This has focused research on energy production processes, supply chains, and reuse and recycling practices.

There are novel and innovative designs for aircraft such as BWB aircraft and solar-powered airships for long journeys that are not time-critical. Such airships are replaced by drones on a very local scale, given that drones meet fully the environmental goals set by government.

Where allowed, remotely piloted and autonomous drones are used for a limited range of applications, only outside urban areas and on demand when no better option is available.

Stringent Testing

Stringent testing, validation and certification are required and mandatory. This follows a global standard, performance-based certification methodology. Digital and virtual qualification and certification techniques and processes are used because they are more efficient and reliable than physical testing. They also avoid the waste generated by testing (all coupons being recycled). Physical testing is only performed when absolutely necessary. Electronic data associated with physical testing are stored electronically for future reference. No physical specimens are stored, with all test samples being recycled, used as new raw material, or as precursors or auxiliary materials for other processes. Therefore, physical testing is also a part of a circular optimisation.

Virtual passports and digital twins are routinely used in the certification process. The underlying data and derived digital tools used are freely available but secure, with systems in place to minimise the risk of fraud.

The research environment

In the Stripping Down scenario, funding for R&D across all sectors is only available to address specific topics aligned with government agendas, priorities and objectives, principally sustainability. This limits the scope for cross-fertilisation because all researchers are addressing the same issues but it creates a very competitive feeling.

R&D and innovation are characterised by slow, gradual and evolutionary development with no step changes or disruptive technologies. Nonetheless, given the global importance of the research topics, cooperation is supported by collaboration frameworks and methodologies and there are several large-scale, long-term, multinational R&D programmes.

R&D is underpinned by standardised, optimised tools and engineering processes. High speed computation and communication networks (wired or wireless) are available at low cost, enabling extensive use of automation and real time computing. Full digitalisation supports free and open-source sharing of research methods, the associated data and models, and outcomes. Intellectual property is freely shared.

Within the sustainability boundaries imposed by the government, the approach taken to R&D is multisectoral and multidisciplinary. Technological R&D is integrated with social sciences and urban planning, as well as fully including citizens in the process using living labs and co-creation spaces. This ensures technology development is aligned to social objectives and personal well-being. Although the path from R&D to deployment is quick, the overall R&D cycle is long.

In such an environmentally-conscious, globally regulated scenario, research infrastructures play a key role for test and deployment encompassing both the technologies themselves and systems integration, in order to be compliant with standards and regulation. When of proven necessity, these infrastructures are funded by government. Simulation tools to optimise mobility, including its environmental impact, the effect of propulsion integration, and regulatory constraints, are a huge topic of research.

Ground test benches for different type of engines and systems (electric motors, electric and electronic network, fuel distribution, equipped tanks, etc.) are needed in order to ensure the required level of safety and security. High power and thermal issues need specific and dedicated ground-based platforms, particularly relating to electrical propulsion and storage, to assess installation, integration and certification issues. Other research facilities needed as support for technology development and integration include:

- gaseous and liquid hydrogen combustion chambers and combustors;
- liquid hydrogen testing unit;
- flight demonstrator of full electric train drive, test rig for testing the electrical power systems.

Safety and security issues are carefully evaluated through a number of targeted research activities and tools:

- intelligence-led, dynamic threat assessment tools to predict, detect, monitor, avoid and counter-act threats;
- physical security, including surveillance and access control;
- a common security simulation environment and tools and assess the performance of security concepts and solutions against present and future threats;
- specific counter measures against a wide range of threats. Furthermore, the evolution of responses against attacks and the protections solutions is based on the high level of standardisation of aviation systems.

Key drivers for aeronautical research and innovation

Vehicles

In the Stripping Down scenario, aircraft are based on a set of top-level aircraft requirements to produce highly standardised vehicles and components. All aircraft are optimised for full cradle-to-cradle sustainability and are manufactured using fully automated, sustainable production processes. Medium and long-distance aircraft are medium-sized, smaller on average than in 2020. Other vehicles have been developed for specific missions, including a limited selection of drones. There are some novel designs and old-fashioned concepts, such as airships, each used when they offer the most sustainable solution.

Vehicles are highly efficient aerodynamically, with very low drag, for reduced energy consumption and lower noise impact. Aerodynamic efficiency and the capacity to adapt to different flying conditions is supported by the ability of the aircraft to change shape and have morphing or flapping wings. Vehicles also often incorporate cloaking capabilities and noise cancellation technology to reduce visual and noise disturbance, especially if operating in proximity to an urban setting, over open areas where tranquillity is valued, such as national parks, or where livestock or wildlife could be negatively impacted. In the case of rotorcraft, all aspects of aerodynamics, mechanical and acoustics design for DEP propellers, including nacelle installation, is focused on noise minimisation. Psychoacoustics analysis, supported also by specific test, supports configuration optimisation with respect to noise.

Aircraft architectures and related systems are of increased complexity, due to electrification and the integration into the aircraft of the electric network, the electronic control boxes, the centralised power and thermal management, the tanks for cryogenic fuels, and other systems. Some technology choices are driven by security criteria, mainly a legacy of the past instability. Benchmarking of the different competing technological evolutions must be carried out in order to identify and choose the most effective security solution and its impact on the airframe.

Vehicles are designed to be modular using approaches optimised for continuously improving sustainability, considering structure and component reuse, remanufacturing, repair and end-of-life aspects. Modularity enables change of purpose between passenger, cargo and combination flights depending on demand. Modularity also facilitates and simplifies MRO.

Circularity practices are fully implemented in the design of aircraft of every type. To minimise waste, design and manufacturing processes are integrated, optimised and fully automated, cradle-to-cradle. Sustainability is the universally applied design principle, based on eco-design, reusability, and maintenance. This is supported by multi-disciplinary design tools and simulations for different technologies, and their integration and optimisation, in particular for propulsion concepts. Full redesign of the aircraft is often needed to incorporate DEP, BLI, BWB, and hydrogen tanks. AI-aided generative design, structural and topological optimisation and biomimicry are supported by full life-cycle analysis with global environmental targets taking precedence over any other optimisation requirements.

Research has resulted in new materials that enable fully sustainable, extremely lightweight structures, which are resilient to impact and extreme (high and low) temperatures, and are self-healing. Self-healing materials are mostly based on smart bio-polymers and nanofillers (nanoparticles, nanofibers, nanowhiskers), resulting in composite systems designed specifically for the requirements of the intended applications. Nanotechnologies are used both for nanocomposite development as well as for the synthesis of the necessary nanofillers. All the by-products of materials synthesis are re-inserted into new production cycles. Waste products and residues are kept at a minimal or zero level. 99% of the chemical by-products (gaseous, liquid, solid) from the manufacturing process are utilised in other technological processes, so that every technology enters a circular loop.

Material models for sustainable, recycled, and bio-based materials, such as wood, and composites with biodegradable resins, and natural fibres, such as wood, bamboo, hemp, flax, basalt and glass, are available. These materials are certified for aeronautical applications.

Thermoplastic matrix composites are fully implemented, due to their high recyclability capabilities and can be used at temperatures up to 400°C and down to -250°C. The manufacturing processes for thermoplastic composites are fully controlled, using in-situ sensors for monitoring and live-recording across the entire process. This results in near-to-zero material loss and the complete elimination of process scrap and product errors. Processing of polymeric composites is controlled at the chemical structural level with the aid of spectroscopic and/or microscopic techniques tracking the evolution of chemical reactions (chemical bond formation, reaction yields, polymerization rate, etc.).

New materials, such as superconductors, ensure the stringent requirements for high power integration can be met. Moreover, smart materials provide the noise, power and thermal control capabilities needed for propulsion integration. AI controls an ultra-efficient embedded electric network, supplying as needed the central power nodes. This network can dynamically reconfigure and optimise energy consumption and signals as required. This saves costs and reduces emissions.

There are two strategies for the sustainable use of materials. One option is to use long-life materials with integrated SHM. The other option is to use (bio-sourced) short-to-medium-life materials adapted to the application, that can be easily replaced. In both strategies the materials are fully recyclable.

Manufacturing is optimised for sustainability and is supported by virtual techniques before commencing actual production, thus limiting the use of resources. Manufacturing is fully automated and makes the maximum use of recycled structures and materials and reused components which come with a “virtual passport”, and a digital twin that catalogues the complete life history and future predictions. Large-scale use is made of additive manufacturing.

Like design and production, MRO is based on globally standardised processes and technology. MRO is predictive and is supported by real-time system and structural health monitoring using sensors integrated, sustainably, within the vehicle. This integration is only allowed if it is possible to replace and remove the sensors to meet recycling and reuse requirements.

Specific components of vehicles and systems are capable of some self-repair when damaged. Everything is modular and easily interchangeable; therefore inspection, maintenance and repair can be automated and supported by robots and smart hangar concepts. 3D printing allows the local production or on-site repair of needed components. Digital twins combine design, manufacturing and use information to determine the condition of the structure or component to predict the necessity to repair or retire the component, trading off between the environmental impacts of repair, reuse and end-of-life. At end of life, everything is recycled or reused in a global fully circular process.

Propulsion

All forms of propulsion are evaluated based on their full environmental impact. Different propulsion solutions are selected depending on the mission. This selection is based on standardised tools to assess the sustainability impacts of specific energy sources combined with different propulsion mechanisms. For complex engine parts, post-design processes are driven by performance and MRO requirements. Stringent safety and security requirements are applied both for personal safety and aircraft security; in particular to electric network self-inspection and reconfiguration and to the control of electromagnetic and high voltage effects.

Various propulsion technologies are considered including:

- electric motors supported by high capacity batteries or fuel cells;
- zero emissions propulsion systems;
- electrodynamic propulsion;
- hydrogen engines, with fully sustainable hydrogen production and onboard storage cells;
- solar propulsion;
- ion and plasma jet engines, in limited applications.

SAFs and hydrogen are produced centrally using efficient sustainable processes.

Drones are based on a variety of single rotor helicopters; multicopters; and tiltwing aircraft; and jet engines with vectored thrust. Drones are fully electric, except in very remote areas, where SAFs are still locally used and are self-produced.

Different solutions are implemented for electrification, mainly based on DEP for ultra-short, short- and medium-range operations with hydrogen solutions being applied to longer flights.

Depending on the propulsion type, integration of the power train and related high-power components (batteries, fuel cells, power distribution, motors, etc.) or the hydrogen tank and related distribution network, present major technological challenges. There are parallel certification issues, especially regarding the integration into the airframe, and with integration, verification, validation and test on ground and on-board technologies. Scalability issues need to be considered, in particular, for the use of technologies derived from other sectors. The regulatory framework has defined global standards and also enables cross-sectorial feeding and technology flow.

Systems

Systems dedicated to security are identified based on their efficiency to face threats and on their complementarity and on the overall consistency of protection. Appropriate criteria and KPIs to assess the quality of security and protection are commonly used and are consistent with the various types of mobility. Benchmarking of the different competing secure systems is carried out to identify and choose the most effective security solutions. These security solutions are upgraded easily, via Plug and Play solutions. Security systems include:

- security threat prediction, surveillance, behaviour monitoring, alerting and decision support, covering, for example, crime, terrorism and pandemic;
- security response, protection procedures, including the management of multiple attacks.

In addition to security, the systems that underpin the Stripping Down scenario are:

- design, manufacturing, test, certification, which are all highly automated, based on AI and robotics. Wide use of digital twins and augmented reality help engineers to quickly conceive and design cutting edge solutions. Collaborative tools driven by the strong innovation framework help in sharing experience and solutions;
- planning, managing and operating the global, multimodal transport infrastructure;
- passenger information systems, providing general travel information;
- weather prediction and alerting tools, e.g. for wind shear, thunder, fog, and sandstorms, using data provided by local sensors and satellites, as input to sophisticated atmospheric models;
- 4D flight planning and dynamic replanning using constantly updated situational data, including weather and security;
- aircraft on-board systems for applications such as 4D navigation (applied to all types of flight), situational awareness, self-separation of traffic, traffic prediction, collision alerting and avoidance, all weather approach and landing, and automatic flight control. For crewed aircraft, systems monitor crew workload and provide decision support whereas they are fully in control of the few autonomous air vehicles. These systems collect, integrate and fuse data collected by the vehicle's own sensors as well as satellite-based and terrestrial navigation (exploiting multi-constellation GNSS), surveillance and weather systems;
- in-flight noise and health monitoring and alerting;
- safety risk-based assessment and mitigation at strategic and operational levels, including, for example, operations such as VTOL;
- systems for the integration and management of both electric and thermal engines using alternative fuels. Factors that need to be addressed include the electric network, electronic controls, thermal and power management, hydrogen tank integration, and others. All propulsion systems require power train integration, in particular the interfaces with the main engine and subsystems; for example, electric motors with mega-Watt level power supplies need specific system and material technologies, e.g. superconducting stators and rotors;
- energy management systems for integrating the different high performance solutions, different types of aircraft. An ITPM system, supported by AI and applied all along the electric network, is required for managing complex architectures. There is a constant need for R&D in the field of:
    - aerodynamic improvements that require secondary on-board power: morphing wings, laminar flow, load alleviation, active flow control;
    - drive trains with potential for TCT, CROR, DEP, BLI propulsion options;
    - multiple distributed heat sources (power electronics, batteries, fuel cells, electric drives, power generation modules, battery management system, cables and buses);
    - changes in heat sinks (potentially less fuel as coolant or it should be liquid hydrogen, composite aircraft skin working as a thermal conserver, need for integrated air intakes, cooling issues inferred by platform or low-altitude operations like queuing times before take-off and landing);
    - prioritizing power assignment to vital functions (power management, failure mode analysis, etc.).

Operational infrastructure

In the Stripping Down scenario, much of the infrastructure for air transport has become integrated into the urban landscape. This design is based on sustainability and social principles, resulting in bio-inspired architecture and circular solutions, including recycled asphalt and energy harvesting roads.

Transport infrastructure is fully standardised and integrated at global level. There a very few airports located outside mega-cities and these cater for transfer between aircraft and public land transport. Most airports have developed into multimodal interchange nodes in the integrated, sustainable architecture for mobility in an integrated transport infrastructure, providing MaaS, together with railway tracks, hyperloop and bus stations. Where needed, specific infrastructure to support air and other transport operations is provided, including runways, vertiports and charging stations for electric vehicles. More generally, airports have developed to enable full and sustainable electrification across all functions. They have also evolved to support other types of vehicle propulsion, such as hydrogen and electrodynamic, used by aircraft and land vehicles.

Reconfigurable Airports

In 2050 terminal buildings are part of the normal built environment, functioning as offices, shopping centres, leisure facilities, hospitality centres and art galleries. These buildings are based on modular, circular principles so that terminals can be resized and repurposed depending on capacity requirements. In addition to generating their own electricity, using photovoltaic cells, wind turbines, geothermal energy and biomass, buildings have been modified to enable the use of multiple sources of energy.

Networks of sensors monitor and collect data on the transport network and the environment, including pollution, contrails, noise, visual disturbance, weather, vehicle status, congestion, health, and safety and security threats. There is also a global safety and security system, based on AI and big data, to predict and manage risks as they emerge along with factors such as disease, climate change, volcanic eruptions and solar storms that affect electronic equipment. Highly resilient networks also provide global communications, navigation and surveillance services. These networks are built of systems-of-systems, comprising terrestrial systems, space-based systems and vehicles themselves, arranged as a FANET. The data collected are fed into processing centres that analyse and synthesise the inputs to produce and publish status reports (nowcasts), and short-, medium- and long-term forecasts. The data are also used to train neural network, AI and quantum computing algorithms.

Air traffic management, from ANSPs and from other ATSs, has all but disappeared. In general, infrastructure such as airport towers and air traffic control centres, is not needed anymore, or smaller scale versions are located in proximity of major airports. ATM fulfils a regulatory function to grant slots for flights based on sustainability criteria and optimises strategic and tactical plans to minimise negative environmental and social impact, and ensure safety, security and efficiency. Once a slot is granted, automation and low levels of traffic mean that aircraft can fly freely in all airspace, navigating and avoiding collisions using on-board systems.

Summary

The research drivers for each dimension – vehicle, propulsion, systems and infrastructure – are summarised in the following table for the Stripping Down scenario.

Dimension	Research themes
Aircraft	Aerodynamics
• tube and wing	• reduced drag
• BWB	• shape-changing/morphing flying surfaces
• airships	• flapping wings
	Structure
	• integrated structural health monitoring
	• integration of energy sources:
	• electrification
	• cryogenic tanks
	• noise cancellation
	• cloaking to reduce visual impact
	Materials
	• lightweight materials
	• high impact and extreme temperatures resistance
	• self-healing
	• smart and bio-polymers
	• nanofillers
	• nanocomposites
	• bio-based materials
	• thermoplastic matrix composites
	• nanotechnology
	• superconductors
	Fully automated, integrated process from design to production
	• virtual testing, certification and qualification
	• digital twins

Dimension	Research themes

Aircraft (continue)
• tube and wing
• BWB
• airships
	Design
	• AI-aided generative design
	• structural and topology optimisation
	• biomimicry
	• full life-cycle analysis
	• modularity
	• sustainability and circularity
	    • eco-design
	    • reusability
	    • maintenance
	• biomimicry
	
	Production/manufacturing
	• full automation
	• virtual manufacturing techniques
	• additive manufacturing
	• reuse and recycling
	    • virtual passport
	    • digital twin

Propulsion	Architectures • distributed electric propulsion (DEP) • boundary layer ingestion Engines • electric motors • zero emission propulsion systems • electrodynamic propulsion • hydrogen engines • ion and plasma jet engines Energy • batteries • fuel cells • hydrogen • solar power

Dimension	Research themes
Systems	Virtual design, manufacturing, test and certification • virtual passports • digital twins Maintenance • self-repair • system and structural health monitoring and alerting • modularity • digital twins • automated inspection, maintenance and repair • smart hangars • 3D printing Planning, managing and operating the global transport infrastructure Passenger information Security • threat prediction • surveillance • behaviour monitoring and alerting • decision support Safety risk assessment and mitigation Passenger screening (security, health and immigration) • biometrics • automation Weather prediction, alerting and avoidance Aircraft on-board automation • 4D navigation • situational awareness • self-separation, collision avoidance and alerting • flight control • decision support Aircraft energy management and control systems • integrated and smart thermal and power management (ITPM)

Dimension	Research themes

Operational infrastructure	Integrated multi-modal transport system
	• multimodal interchange nodes
	• support use of multiple energy sources
	    • electricity
	    • liquid hydrogen
	• climate-optimised flying
	
	Communications, navigation, surveillance and monitoring system with terrestrial, satellite and flying components
	
	Global safety and security system using AI and big data

Scenario 4: Optimising Together

...aviation: unlimited freedom in a world of common purpose, collaboration and cohesion

A world characterised by unification and harmony; global cooperation and collaboration; global legal and institutional frameworks; high stability and growth; sustainability; market-driven economies and liberalisation; high standardisation and confidence.

Mobility is growing and is fully sustainable. Different aviation solutions are available for all journey segments from UAM through formation flying to suborbital flights.

How we fly in this scenario

In the Optimising Together scenario, aviation is one component of the overarching global MaaS concept providing unlimited freedom and flexibility.

Travel is organised and managed through one global framework, overseen by the global institutions. There is a uniform, light-touch global regulatory system covering safety, security, sustainability, and health standards. Minimal local variations are allowed but are harmonised. Borders are fully open. International travel only requires the minimum checking and scrutiny. Supported by the light-touch regulatory regime, demand for travel is high, driven by increases in wealth; by the open, stable and outward-looking nature of global society; by the high confidence of the average traveller; and by the achievement of highly sustainable transport systems. All concerns related to pollution, noise and unsustainable practices linked to transport have been solved or are being addressed using inclusive, collaborative mechanisms in cooperation with citizens and passengers. The very low negative impact and positive public view of aviation means that it competes effectively, as an integral part of a seamless, intermodal network, with virtual technologies for both business and leisure purposes.

The full spectrum of fully sustainable travel solutions is provided. Available transport modes include suborbital vehicles for very long journeys, innovative design aircraft (BWB, flying-V, quad- and double-bubble, etc), high-speed and conventional rail, hyperloop, electric buses, cars, bicycles and scooters, and the full range of UAM solutions for public and personal travel.

Travellers have almost infinite freedom to design their personalised, complete door-to-door journey, and to reconfigure en-route if needed. The passenger has full visibility of all options and can make choices depending on personal preference, which include but not be limited to price, journey time and convenience.

Dedicated themed journeys can also be selected. For example, luxury journeys have many options such as:

- invisible security, health and immigration checks being performed either at home or en-route;
- optimum comfort in the cabin, which minimises external noise, vibration and turbulence;
- advanced, personalised entertainment systems; and continuous, high-bandwidth connectivity.

Many other options are also provided, including ultra-healthy trips; "old-time" experiences using vintage aircraft and traditional service; highly sustainable travel; adventure rides using very fast jets; family options; no-children options; and so on.

There is absolutely no tolerance towards pollution, noise and visual disturbance that used to be generated by transport. These impacts have been totally eliminated. All transport modes are treated equally using a standard set of KPIs and standardised global climate impact models to inform the passenger in the design of the door-to-door journey. To support this zero-tolerance, aviation's environmental impact is assessed on a cradle-to-cradle basis using standard KPIs from sustainable environmental, social and governance principles. Full life-cycle assessment analyses the entire impact of the vehicle, its systems and energy sources, including energy production and storage mechanisms, based on cradle-to-cradle approach.

As well as flying at conventional tropospheric and stratospheric altitudes, different aircraft types operate from close to the ground, for UAM, and up to suborbital altitudes for fast, long-range journeys. Aircraft fly at subsonic, supersonic and hypersonic speeds. At low altitudes, especially around urban areas, air traffic is very dense and complex, serving an asymmetrical and heterogeneous mix of vehicles. This mix includes aircraft transiting to and from higher flight levels at suborbital and stratospheric flight levels, as well as a huge variety of UAM vehicles. At higher altitudes, there is a mix of different aircraft types, ranging from airships to supersonic vehicles, often flying on dense routes between major population centres. Drones are used, generally at low altitudes, for many applications, including:

- geospatial applications, mapping and surveying;
- monitoring, inspection and management of, for example:
  - utility distribution networks, such as water pipes and electricity power lines, to detect leaks, defects, damage, threats and hazards;
  - road and rail networks to manage congestion, detect damage, e.g. to overhead cables, tracks and road surfaces, as well as threats and hazards, such as vegetation encroachment;
  - remote, offshore, inaccessible and hazardous sites.
- land and sea-use management, including:
  - agriculture, including crop spraying, seed sowing and fertilisation;
  - forestry, including forest fire detection and response;
  - fisheries monitoring and protection;
  - monitoring environmentally sensitive areas;
  - crop monitoring;
  - public right-of-way assurance.
- humanitarian aid and disaster response, covering, for example:
  - search and rescue;
  - assessing damage from natural disasters;
  - medical aid and food distribution.
- weather and climate monitoring, including:
  - weather observation;
  - frost heave, snow and ice measurement.
- conservation in game reserves and the wilderness:
  - migratory tracking;
  - biodiversity assessment.

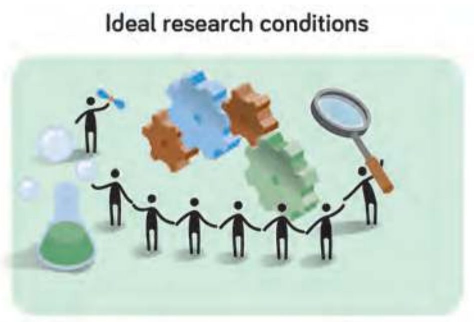
In addition, drones and HAPS are used to support communications, navigation and mapping, surveillance and monitoring, and earth observation.

All aircraft in this scenario are fully autonomous. A very few leisure aircraft are operated by a single pilot supported by automated systems and decision support tools in the cockpit for recreational purposes only. Automated on-board systems are used to ensure separation between all aircraft.

Planning and management of air traffic is integrated into global systems and processes for management of MaaS with focus on enabling many fully flexible personal journeys from origin to destination as defined by the traveller. Planning systems encompass individual journeys, local, national and global networks. Individual route planning is climate-optimised at local, national and global network level using a mixture of hub and spoke, and point-to-point operations.

Airspace has been restructured to cater for increased demand and the massive diversification of aircraft types operating in close proximity to each other. The high demand for aviation means that airspace and interchange nodes can be congested and the traffic mix very diverse and complex. Capacity needs to be constantly managed. To facilitate navigation in the air transport system and to support maintenance and other tasks, a high number of specialised sensors are integrated into vehicle structures.

A standard, performance-based certification methodology using virtual qualification and certification techniques is applied and is more efficient and reliable than physical testing. The certification process is based almost exclusively on virtual passports and digital twins. The underlying data and derived digital tools used are freely available but secure, with data systems in place to minimise the risk of fraud. Materials are also developed virtually and tested in a virtual environment prior to one final loop of real full-scale testing. Physical testing is performed strictly only when and where necessary. Electronic data (e.g. numerical data, parameters, measured values, video and photo recording) associated with the physical testing are stored electronically for future reference, but no physical specimens are stored, all test samples being recycled and used as new raw material, or as precursors or auxiliary materials for other processes. Therefore, physical testing is also a part of circular optimisation. Certification for recycled materials has been fully achieved, by support of virtual allowable, virtual material design, virtual manufacturing and virtual testing.



The research environment

In the Optimising Together scenario, R&D, and innovation are characterised by global cooperation, supported by collaboration platforms and methodologies based on the cornerstone of a universally applied and high performance innovation framework. Full digitalisation and common agreements on the handling of intellectual property enables free sharing of research methods, the associated data and models, and outcomes.

The approach taken to R&D is multisectoral and multidisciplinary. Technological R&D is integrated with social sciences and urban planning. Citizens are fully included in the process using living labs and co-creation spaces. This ensures technology development is aligned to social objectives and personal well-being. This cross-sector and free-thinking approach enables rapid developments.

R&D is well-funded. As well as proactively generating disruptive step-changes in technology, it is also highly reactive to perceived problems and to future challenges. There is a short R&D cycle, enabled by excellent facilities, tools and models, that rapidly delivers high TRL results. There is also a continuous uptake of low TRL technologies and basic research to be applied at higher TRL or at industrial scale. This is facilitated by fast prototyping, and local digital and virtual certification processes that are flexible and adaptable.

R&D is underpinned by standardised, optimised tools and engineering processes. The key enablers of high performance computing and communication networks (wired or wireless) are available at low cost, allowing an extensive use of automation and real time computing, and the fusion of huge volumes of data. The outputs of R&D require stringent testing, validation and certification following a standard, performance-based certification methodology using digital and virtual certification techniques.

Facilities are widely available for virtual, ground and airborne bench testing and system validation, as well as flying test beds. Ground test benches are provided for the different type of systems (electric motors, electric and electronic network, fuel distribution, equipped tanks, etc.) to ensure the required level of safety and security. High power and thermal issues need specific and dedicated on ground platforms, to assess installation, integration and certification issues. To address the challenges of hypersonic flight, specialised wind tunnels are needed, starting with digital wind tunnels for the early stages of development ultimately through to wind tunnels and flying tests.

Overall, the capabilities needed as support for technology development and integration include but are not limited to:

- high performance computing platforms and very high-speed digital networks, wired and wireless;
- simulation tools to optimise mobility, including environmental impacts, propulsion integration effects, regulatory constraints and growth;
- multi-disciplinary design tools, simulations and test-beds for different technologies, their integration and optimisation, in particular for vehicle and propulsion concepts (DEP, BLI, BWB, hydrogen tank integration, etc.);
- gaseous and liquid hydrogen combustion chambers and combustors;
- multidisciplinary optimisation methods and metrics for propulsion configurations such as boundary layer ingestion and distributed propulsion;
- ground test rigs and flying test-beds, e.g. for hydrogen engines and safety testing of batteries;
- flight demonstrators for full electric train drive;
- ground and airborne electrical power systems test rigs;
- propulsion testing facility for developing and testing materials;
- large scale icing wind tunnel;
- digital and flying hypersonic wind tunnels;
- power integration test rig.

The widespread application UAM and the fast R&D cycle mean that drones and UAM vehicles are the ideal, real-life, platform to implement innovations and to assess their impact, especially with regard to the integration of UAM in the urban setting, and its impact on infrastructure for refuelling, recharging, maintenance and passenger operations.

In such an open, cross-sectorial collaborative environment, there are also many high TRL spin-offs from other research sectors. Such potential spin-offs can apply technology into aircraft, in particular for new propulsion systems, e.g. marine bio-fuel engines for large aircraft, and high voltage rail technologies into electric networks.

Key drivers for aeronautical research and innovation

Vehicles

In the Optimising Together scenario, aircraft have become smaller, more diverse and greater in number to cater for the increased number of passenger journeys. Different types of air vehicle have been developed for specific missions.

The range of vehicles includes UAM vehicles for short journeys, and drones and HAPS for specific applications. There are also many different types of aircraft for longer journeys including optimised conventional designs as well as hybrid tube-wing, BWB, double- and quad-bubble, as well as improved concepts such as ground effect vehicles (GEV) and airships.

Vehicles are highly efficient aerodynamically, with very low drag, for higher speeds, reduced energy consumption and lower noise impact. Aerodynamic efficiency and the capacity to adapt to different flying conditions is supported by the ability of the aircraft to change shape and have morphing or flapping wings. Vehicles also incorporate cloaking capabilities and noise cancellation technology to reduce visual and noise disturbance, especially if operating in proximity to an urban setting, over open areas where tranquillity is valued, such as national parks, or where livestock or wildlife could be negatively impacted. In the case of rotorcraft, all aspects of aerodynamics, mechanical and acoustics design for DEP propellers, including nacelle installation, is focused on noise minimisation. Psychoacoustics analysis, supported by specific tests, supports configuration optimisation with respect to noise.

Aircraft architectures and related systems are of increased complexity, due to electrification and the integration into the aircraft of the electric network, electronic control boxes, centralised power and thermal management, tanks for cryogenic fuels, and other systems. Some technology choices are driven by security and safety criteria. Benchmarking of the different competing technological evolutions must be carried out in order to identify and choose the most effective security solution and its impact on the airframe.

Vehicles are designed using approaches optimised for continuously improving sustainability, considering structure and component reuse, remanufacturing, repair and end-of-life aspects. Circularity practices are fully implemented in the design of aircraft of every type. To eliminate waste, design and manufacturing processes are integrated, optimised and fully automated, cradle-to-cradle. Sustainability is the universally applied design principle, based on eco-design, reusability, and maintenance. This is supported by multi-disciplinary design and simulation tools for the integration and optimisation of different technologies. AI-aided generative design, structural and topological optimisation and biomimicry are supported by full life-cycle analysis with global environmental targets taking precedence over any other optimisation requirements.

Vehicles are designed to minimise the effects of vibration, turbulence and g-forces in the cabin, which are designed so that acceleration loads for supersonic, hypersonic and suborbital flight are not transferred to the passengers. High-speed vehicle structures use the forces associated with these flight loads, along with friction heating, as a source of energy to boost onboard power supplies.

The aircraft cabin ensures that the passenger travels in absolute comfort with all of the luxuries of home, including entertainment systems, based on virtual and augmented reality with full and highly reliable, high speed connectivity throughout the journey. There is full and highly reliable, high speed connectivity throughout the journey. Motion, vibration and noise cancelling systems are used to avoid air sickness and to improve passenger comfort, especially in UAM.

For longer flights in hypersonic or suborbital aircraft, there are wellness, mindfulness and stress-calming systems and services available in the cabin to reduce any side effects of this type of flight. Depending on the type of journey that the passenger has selected, there may be cabin crew or robots on-board to emphasise the customer experience.

Material research has resulted in new materials which enable fully sustainable, extremely lightweight structures that are resilient to impact, extreme (high and low) temperatures, and are self-healing. Self-healing materials are mostly based on smart bio-polymers and nanofillers (nanoparticles, nanofibers, nanowhiskers, etc), resulting in composite systems designed specifically for the requirements of the intended applications. Nanotechnologies are used both for nanocomposites development as well as for the synthesis of the necessary nanofillers.

Material models for sustainable, recycled, and bio-based materials, such as wood, and composites with biodegradable resins and natural fibres, such as wood, bamboo, hemp, flax, basalt and glass, are available. As mining for virgin raw materials is not allowed, vehicles are constructed from recycled materials from aviation junkyard and urban mining. To enable this, certification of recycled materials for aeronautical applications has been fully achieved, by support of virtual allowable, virtual material design, virtual manufacturing and virtual testing.

Thermoplastic matrix composites are fully implemented, due to their high recyclability capabilities and can be used at temperatures up to 400°C and down to -250°C. The manufacturing processes for thermoplastic composites are fully controlled, using in-situ sensors for monitoring and live-recording live across the entire process. This results in near-to-zero material loss and the complete elimination of process scrap and product errors. Processing of polymeric composites is controlled at the chemical structural level with the aid of spectroscopic and/or microscopic techniques tracking the evolution of chemical reactions (chemical bond formation, reaction yields, polymerization rate etc). These materials have the capability to integrate sensors for real-time structural health monitoring to facilitate MRO, as well as external environmental and social impact monitoring. Integration of sensors in structures is enabled because it is possible to replace and remove the sensors to meet recycling and reuse requirements in line with sustainability objectives.

New materials, such as superconductors, ensure that the stringent requirements for high power integration can be met. To enable additional product functionality, smart materials and functionally graded materials are implemented widely. Challenges related to the reuse or recycle of those materials have been resolved.

Smart materials provide the noise, power and thermal control capabilities needed for propulsion integration. AI controls an ultra-efficient embedded electric network, supplying central power nodes. This network can dynamically reconfigure and optimise energy consumption and signals as required. This saves costs and reduces emissions.

There are two strategies for the sustainable use of materials. One option is to use long-life materials with integrated SHM. The other option is to use (bio-sourced) short-to-medium-life materials adapted to the application, that can be easily replaced. In both strategies the materials are fully recyclable.

Circular manufacturing technologies are fully developed. All processing technologies are interconnected in terms of raw materials, secondary products and final products. All by-products are re-inserted into other production cycles. Waste products and residues are kept to a minimal or zero level. Virtually all of the chemical by-products (gaseous, liquid, solid) from the manufacturing process are utilised in other

technological processes, so that every technology enters a circular cycle. Products that have reached their end-of-life are reused as second-hand parts in aviation or other industries, which are strongly connected to aviation by environmental related regulations. All technological processes are balanced, cross-industry, from the environmental perspective. By-products resulting from technologies associated with one industry are quickly identified as chemical components of technological processes associated to other industries.
This ensures minimum to zero waste of chemical compounds and products.

Manufacturing is based primarily on virtual techniques, is fully automated and makes the maximum use of recycled structures, materials and reused components, which come with a "virtual passport", and a digital twin that catalogues the complete life history and predicts future performance. Large-scale use is made of additive manufacturing, often to produce whole aircraft.

Virtual manufacturing technologies predict changes to variable parameters (material and energy consumption, secondary compounds quantity and quality) as well as error troubleshooting, so that physical manufacturing is a fully controlled process.

Maintenance, repair and overhaul

Like design and production, MRO is based on globally standardised processes and technology. MRO is predictive and is supported by real-time system and structural health monitoring using sensors integrated within the vehicle. Components of vehicles and systems are capable of a degree of self-repair when damaged. Everything is modular and easily interchangeable. Inspection, maintenance and repair are automated and supported by tools and techniques, including AI, drones, smart hangars and 3D printing for producing repairs or for on-site on-part repair. Given the amount of information generated from design, through manufacturing, during use and maintenance, digital twins for the entire vehicle and each component are generated and constantly updated. They combine design, manufacturing and use information to determine the condition of the structure or component to predict the need to repair or retire the component, trading off between the impacts of repair, reuse and end-of-life.

At end of life, everything is recycled or reused in a fully circular process.

Propulsion

Sustainability considerations mean that fossil fuels are no longer used and aircraft propulsion has zero environmental or health impact enabled by research on alternative engines and energy production processes and supply chains.
Full electric technologies are available all over the world and are used in full electric aircraft for short and medium range journeys. There is a wide variety of fully sustainable propulsion technologies available for longer journeys, that can be selected according to specific criteria. Options include green supersonic and hypersonic engines, electrodynamic and ion propulsion and highly efficient jet engines.

SAFs and hydrogen are produced centrally using efficient sustainable processes. The technologies used for conventional, supersonic, hypersonic and suborbital aircraft include:

- electric motors supported by high capacity, sustainable batteries or fuel cells;
- zero emissions propulsion;
- electrodynamic propulsion;
- green supersonic and hypersonic engines;
- hydrogen engines, with fully sustainable hydrogen production and onboard storage cells;
- solar propulsion;
- ion and plasma engines.

UAM is based on a variety of conventional single rotor helicopters, multicopters, tiltwing aircraft, and engine with vectored thrust. In all cases, UAM aircraft are fully electric.

Different solutions are implemented for electrification, mainly based on DEP for regional and short-medium range operations through to hydrogen solutions for long range flights. Integration of the power train and related high-power components (batteries, fuel cells, power distribution, motors, etc.) or of the hydrogen tank and related distribution network into the aircraft, presents major technological challenges. The certification challenges regard the integration into the airframe, and the verification, validation and test of on-ground and on-board technologies. Scalability issues are regularly considered, in particular, for the use or technologies derived from other sectors. The regulatory framework has defined global standards and also enables cross-sectorial feeding and technology flow.

This open scenario enables cross-sector knowledge and technology flow, and integration, resulting in reduced time to market and in a strong innovation cycle; an example can be miniaturization from the space and ICT sectors to help the integration of the electric network into the aircraft.

Systems

Systems dedicated to security are identified based on their efficiency to face threats and on their complementarity and on the overall consistency of protection. Appropriate criteria and KPIs to assess the quality of security and protection are commonly used and are consistent with the various types of mobility. Benchmarking of different competing secure systems is carried out in order to identify and choose the most effective security solutions. Security solutions are upgraded easily, via Plug and Play solutions. Security systems include:

- security threat prediction, surveillance, behaviour monitoring, alerting and decision support, covering, for example, crime, terrorism and pandemic;
- security response, protection procedures, including the management of multiple attacks.

In addition to security, the main areas where systems are applied in the Optimising Together scenario include:

- design, manufacturing, test, certification and MRO, which are all highly automated, based on AI and robotics. Wide use of digital twins and augmented reality helps engineers to conceive and design cutting edge solutions quickly. Collaborative tools driven by the strong innovation framework help in sharing experience and solutions;
- planning, managing and operating the fully integrated, global, multimodal transport infrastructure, including system wide information management (SWIM) based on system wide big data;
- planning and managing concurrent global door-to-door journeys, utilising intelligence available from historical, real-time and forecast system-wide (big) data and the outputs from highly accurate and reliable weather models and individually optimised 4D trajectories;
- planning and managing large fleets of different vehicle types;
- controlling and optimising the cabin environment using intelligent systems, including vibration, motion and noise cancelling, inflight entertainment using virtual and augmented reality and other immersive technologies, automated cabin service and projection of real-time outside views instead of windows;
- 4D flight planning and dynamic replanning using constantly updated situational data, including congestion, weather and security;
- weather prediction and alerting tools at micro, meso and macro scales ranging from prediction of wind flows around buildings for safe UAM, through wind shear, thunder, fog and sandstorm events, to jet stream and high altitude winds. Real-time and historical data are provided by crowd-sourcing from vehicles themselves, local sensors, satellites and HAPS and is processed using algorithms based on AI, machine and deep learning;
- aircraft on-board systems for applications such as 4D navigation and related autonomous integrity (applied to all types of flight from low altitude to sub-orbital), situational awareness, self-separation of traffic, traffic prediction, collision alerting and avoidance, all weather

approach and landing, and automatic flight control. For crewed aircraft, systems monitor crew workload and provide decision support whereas they are fully in control of autonomous air vehicles. These systems collect, integrate and fuse data collected by the vehicle's own sensors as well as satellite-based (exploiting multi-constellation GNSS) and terrestrial navigation, surveillance and weather systems;

- in-flight noise and health monitoring and alerting;
- safety risk-based assessment and mitigation at strategic and operational levels, including, for example, operations such as VTOL and suborbital flight, and in highly complex and congested traffic areas;
- passenger information systems, including:
    - gathering and provision of urban intelligence for journey planning and optimisation;
    - personalisation of services to individual passengers, including transport mode choices optimised according to passenger defined criteria;
    - automatic reconfiguration of journeys in the case of disruption;
    - general travel information.
- systems for the integration and management of both electric and thermal engines using alternative fuels. Factors that need to be addressed include the electric network, electronic controls, thermal and power management, hydrogen tank integration, and others. All propulsion systems require power train integration, in particular the interfaces with the main engine and subsystems. For example, electric motors with mega-Watt level power supplies need specific system and material technologies, e.g. superconducting stators and rotors;
- energy management systems for integrating the different high performance solutions, different types of aircraft. An ITPM system, supported by AI and applied all along the electric network, is required for managing complex architectures. There is a constant need for R&D in the field of:
    - aerodynamic improvements that require secondary on-board power: morphing wings, load alleviation, active flow control;
    - drive trains with potential for TCT, CROR, DEP, and BLI propulsion options;
    - multiple distributed heat sources (power electronics, batteries, fuel cells, electric drives, power generation modules, battery management system, cables and buses);
    - changes in heat sinks (potentially less fuel as coolant or it should be liquid hydrogen, composite aircraft skin working as a thermal conserver, need for integrated air intakes, cooling issues inferred by platform or low-altitude operations like queuing times before take-off and landing);
    - prioritizing power assignment to vital functions (power management, failure mode analysis, etc.).

Specifically for UAM, another area of system research relates to trade-off between on-board computing and terrestrial computing, considering:

- terrestrial high performance computing data centres optimised for sustainability and circularity;
- contingency needs for autonomy to enable the vehicle to continue to fly safely (onwards to the destination or divert to the nearest vertiport) if connections are lost to GNSS or to any other network (e.g. 5G-6G-7G-8G);
- the cost of the on-board computing capacity;
- the available bandwidth on the networks used.

Most data processing and computing are done in terrestrial global information centres. These centres provide information (e.g. weather, traffic prediction, safety and security predictions, pollution and noise) to all vehicles flying within their coverage area. On-board computing concentrates on autonomous flying, refining local and short-term and contingency aspects.

In general, highly trusted automated systems have resulted in a change of balance of the responsibility for decision-making from the human to the machine, with the human playing a very limited monitoring role but with the authority to over-rule the system if required.

The systems that underpin the Optimising Together scenario have resulted from extensive mathematics and neuro-science research into AI, machine learning and deep learning supported by full digitalisation, high performance computing and the collection, integration and synthesis of data from all elements of the transport system and beyond. This research has not only addressed the systems themselves but also the supporting test, validation and certification technique and processes, as well as addressing all concerns on cyber security and vulnerability against other external hazards and threats. Ethical questions on the use of AI and harvesting large amounts of, sometimes personal, data have also been addressed. Cyber security evolves continuously to meet ever changing threats. Those are particularly relevant in design, manufacturing and MRO aspects, which are all highly automated, based on AI learning and robotics applications.

Broader, comprehensive, transport system

Operational infrastructure

In the Optimising Together scenario, transport infrastructure is fully sustainable, standardised and integrated at global level. It is adaptable to integrate different energy sources and supports full door-to-door mobility, delivering the MaaS concept.

The ground-based infrastructure for air transport is unobtrusive has become integrated into and is indivisible from the local environment in both urban and rural areas. Urban areas have been redesigned to include the third dimension in the multi-level transport system. The transport infrastructures are based on sustainability and social principles, resulting in bio-inspired architecture and circular solutions, including recycled asphalt and energy harvesting roads.

Air transport infrastructure includes nodes where interchange can take place between transport modes. There is a large mix of these interchange nodes ranging in size from large multimodal hubs to smaller local facilities. All of the nodes cater for seamless transfer between land transport, such as rail and hyperloop, and UAM solutions. They all have landing parks (vertiports) for UAM and recharging stations for electric vehicles. More generally, airports have developed to enable full and sustainable electrification across all functions. They have also evolved to support other types of vehicle propulsion, such as hydrogen and electrodynamic, used by aircraft and land vehicles. In addition, where needed, specific additional infrastructure to support other air operations is provided, including runways, and launch and landing pads for suborbital flights. The nodes are designed to be readily reconfigurable to cater for multimodal transport designs and solutions.

At those nodes, there is no need for verification processes, such as check-in, security and immigration, because all passengers are actively monitored continuously and invisibly in an ethical and socially acceptable way in everyday life. This means that airport buildings in the conventional sense are no longer needed and interchange nodes are part of the normal built environment, as offices, shopping centres, leisure and entertainment complexes, hospitality centres and art galleries. These buildings are based on modular, circular principles so that they can be resized and repurposed depending on capacity requirements. In addition to generating their own electricity, using photovoltaic cells, wind turbines, geothermal energy and biomass, buildings have been modified to enable multiple sources of energy.

There is a global environment monitoring network based on the integration of multiple sensors, on the ground, on air, sea and land vehicles themselves, in the stratosphere and space-based. These sensors monitor and collect data on the transport network and the environment, including pollution, contrails, noise, visual disturbance, weather, vehicle status, congestion, health, and safety and security threats. The data collected are fed into processing centres that analyse and synthesise the inputs to produce and publish status reports (nowcasts) and short-, medium- and long-term forecasts. The data are also used to train neural network, AI and quantum computing algorithms.

There is also a global safety and security system, based on AI and big data, to predict and manage risks as they emerge, covering factors such as disease, climate change, volcanic eruptions, and solar storms that affect electronic equipment.

Airspace is integrated at global level and is managed to cater for the extremely high levels of complex and heterogeneous traffic. Airspace is extended to enable the use of suborbital trajectories and corridors as part of the air transport system. Traditional ATM has developed into U-space management and extends from the ground to space and is provided as an integrated component of the management of MaaS. U-space management optimises strategic and tactical plans as well as dynamically managing operations to ensure safety, security and efficiency. It caters for the complex, asymmetrical and heterogeneous mix of vehicles, from suborbital craft to flying cars, all occupying the same congested and high density airspace. U-space management is fully autonomous and is based on AI. It is self-organised as a cooperative and distributed system with various levels of responsibility from the system in its entirety down to individual vehicles. It collects data from, and communicates through, a network of sensors, including terrestrial monitors, HAPS and satellites as well as the air vehicles themselves, arranged as a FANET.

Summary

The research drivers for each dimension – vehicle, propulsion, systems and infrastructure – are summarised in the following table for the Optimising Together scenario.

Dimension	Research themes

Aircraft
• tube and wing
• BWB
• flying V
• double bubble
• quad bubble
• supersonic
• hypersonic
• sub-orbital
• GEV
• UAM
• drones
• HAPS
• airships
	Aerodynamics
	• reduced drag
	• shape-changing/morphing flying surfaces
	• supersonic, hypersonic and suborbital capability
	
	Structure
	• integrated sensors
	    • real-time structural health monitoring
	    • for U-space management
	    • environmental and social impact monitoring
	• integration of energy sources:
	    • electrification
	    • cryogenic tanks
	• cloaking to reduce visual impact
	• friction heating as an energy source
	• noise, vibration and motion cancelling
	• g-force reduction
	
	Materials
	• noise, vibration and g-force reduction
	• friction heating as an energy source
	• (ultra) high and low temperature materials
	• recycled materials
	• lightweight materials
	• self-healing
	    • smart and bio-polymers
	    • nanofillers
	• nanocomposites
	• bio-based materials
	• nanotechnology
	• superconductors
	• high impact resistance
	• smart materials
	• functionally graded materials
	•
	•

Dimension	Research themes

Aircraft (continue)
• tube and wing
• BWB
• flying V
• double bubble
• quad bubble
• supersonic
• hypersonic
• sub-orbital
• GEV
• UAM
• drones
• HAPS
• airships
	Fully automated, integrated process from design to production
	• virtual testing, certification and qualification
	• digital twins
	
	Design
	• AI-aided generative design
	• structural and topology optimisation
	• biomimicry
	• full life-cycle analysis
	• modularity
	• sustainability and circularity
	    • eco-design
	    • reusability
	    • maintenance
	
	Production/manufacturing
	• full automation
	• virtual manufacturing techniques
	• additive manufacturing
	• reuse and recycling
	    • virtual passport
	    • digital twin
	• biomimicry

Propulsion	Architectures • distributed electric propulsion (DEP) • boundary layer ingestion Engines • electric motors • zero emissions propulsion systems • electrodynamic propulsion • hydrogen engines • ion and plasma jet engines • green supersonic and hypersonic engines Energy • batteries • fuel cells • hydrogen • solar power

Dimension	Research themes
Systems	Maintenance • self-repair • system and structural health monitoring and alerting • modularity • digital twins • automated inspection, maintenance and repair • smart hangars • 3D printing Planning, managing and operating the integrated, global, multimodal transport infrastructure Planning and managing concurrent door-to-door journeys Complex vehicle fleet planning and management Passenger information Cabin environment optimisation • personal entertainment • continuous high-speed connectivity • motion and vibration control • noise cancelling • cabin service robots Security • threat prediction • surveillance • behaviour monitoring and alerting • decision support Safety risk assessment and mitigation Aircraft on-board automation • 4D navigation • master and slave formation flying • situational awareness • self-separation, collision avoidance and alerting • flight control • decision support for crewed flights (long distance) • full autonomy for UAM

Dimension	Research themes
Systems (continue)	Aircraft energy management and control systems • integrated and smart thermal and power management (ITPM) UAM • trade-off between on-board and terrestrial computing • contingency/resilience for system failures U-space management • automation • autonomy Supporting capabilities • high performance computing • high speed connectivity • big data • AI, machine learning and deep learning • robotics • cyber security, encryption • plug and play solutions

Operational infrastructure	Integrated multi-modal transport system
	• multimodal interchange nodes
	• (climate) optimised airspace structure
	• support use of multiple energy sources
	    • electricity
	    • liquid hydrogen
	
	Fully autonomous, global, integrated U-space management system, including monitoring and data acquisition

The Future of Aviation for EREA

Common Themes

Aviation is present in all scenarios. Whether limited to fulfilling the human dream of flying or as major means of transport, aviation has become so much of a feature of the European and global way-of-life, that its removal is inconceivable. Nonetheless, aviation's success, and potential growth, is contingent on widespread public acceptance, which requires it to **eliminate actual negative impacts**, as well as to **overcome unfavourable societal perceptions**. Aviation must also be highly competitive compared to its alternatives, be they other transport modes or substitutes for travel altogether.

Despite some marked differences, there is a number of common, emerging themes that define the future aviation landscape and associated research across most or all scenarios. These common themes are good indicators for the direction of future research.

1. The **variety of vehicle types will increase** from the tube and wing, and single or double rotor concepts so prevalent today. For short flights UAM vehicles and drones will be used extensively in a wide range of configurations including multicopters and tiltwings, resulting in many more short- and vertical-take-off and landing aircraft. For longer journeys, the types of aircraft used will expand to include emerging concepts, such as BWB, flying-V, and double and quad bubbles. There will also potentially be other advanced configurations, including ground effect vehicles, as well as the reinvention of older ideas, such as airships.

2. These aircraft will increasingly use **multiple different sustainable energy sources**. These energy sources will include high performance batteries, fuel cells and solar energy for (hybrid) electric vehicles, and possibly even nuclear power. Ultimately, hydrogen engines, electrodynamic propulsion, or ion and plasma jet engines will be used for longer flights. The challenges of the integration of these energy sources into the vehicle will be overcome. Either before these technologies are mature or as an alternative, other solutions will include synthetic jet fuels and alternative liquid fuels, such as methane and liquified natural gas, using environmentally optimised high-bypass turbofan engines.

3. The **materials** used to make vehicles will have improved properties, such more lightweight and higher impact and temperature resistance. The distinction between material and structure and system will become narrower, given the possibilities offered by smart materials, self-healing materials and functionally graded materials. Material choices will become more varies, ranging from bio-based and recyclable, up to include nanotechnology and superconductors as well as different sorts of composites.

4. There will be a general trend to a**utonomy and automation** in all parts of the aviation sector, from design and manufacturing through vehicle operation and MRO to air traffic control. Onboard the airplane, automation will range from providing the crew with decision support to supporting full autonomous flight. Air traffic control will evolve into fully autonomous U-space management of extremely complex and busy airspace containing a very diverse mix of vehicles. As well as overcoming the technical challenges associated with autonomous systems and operation – including test, qualification and certification, safety and security assurance, human factors considerations and resilience to system failures – there will be a high level of public confidence in autonomous flight, and autonomous technologies.

5. Aviation will remain the **safest and most secure** means of transport through the application of risk-based assessment and mitigation techniques. Security systems will predict and identify emerging threats. Surveillance

systems will be used to track threats, applying behaviour monitoring and prediction techniques; and sophisticated decision support tools will assist in defining actions to counter the threats. In the massively connected world, cyber security will remain a priority with data and information being protected using increasingly sophisticated encryption and blockchain. Safety systems will identify and mitigate all potential hazards with increasing accuracy and reliability, including micro-weather threats to UAM around buildings, the dispersion of volcanic ash clouds in the stratosphere and pandemic health threats on-board aircraft and in airports.

6. Aviation will still be supported by **operational infrastructures**. Airports will evolve and adjust to different volume of traffic or to new vehicles, and also ensure connectivity with other means of transportation. Other needed infrastructures will include global position, navigation, timing and communications services, based on satellites, HAPS, ad-hoc networks of all types of vehicles and terrestrial systems. There will be environment monitoring network and safety and security systems, based on the integration of multiple sensors, on the ground, on air, sea and land vehicles themselves, in the stratosphere and space-based as well and supported by artificial intelligence and big data.

7. **MRO** will remain critical to the safe and efficient operational operation of air vehicles. In some scenarios, MRO efficiency and effectiveness will be increased by using structural health and other monitoring systems and sensors and machine learning to enable predictive maintenance. In others current MRO practices will be aided by other advanced techniques such as automated inspection, smart hangars, digital twins and 3D printing for on-site spare parts manufacturing.

8. A focus on **passenger-centric systems** will be fundamental for aviation, whether to satisfy the customer needs or to guarantee safety and security. Tools will provide information to enable the design and execution of personal journey and to assist the passenger in planning the flight based on personal preference and by considering a multitude of other alternatives. The same systems or data will also be used for security purposes, to support in depth security check or unobtrusive or invisible passenger security checking at home or at the airport.

Contrasting Themes

As well as common themes, the scenarios also highlight a number of research areas and themes where developments might or might not occur, depending on how the world evolves. A watch needs to be kept on the signposts for world development to assess if and when these areas and themes become priorities.

1. The transition of aviation towards a more and more integrated **multimodal transport system-of-systems** delivering MaaS, will depend on several factors, particularly of social relevance. This is mainly given to the major adjustments needed to enable the planning and execution of seamless, door-to-door, journey. In addition to the expansion to multimodal capability of the passenger-centric systems mentioned above, aviation's ground infrastructure – airports and vertiports – will require changing into multimodal interchange nodes and this can only be achieved in coordination between society and governments.

2. Although **UAM** will undoubtedly play a role in the future of aviation, the degree to which it will be taken up by 2050 and the type of missions are uncertain. In some scenarios, some UAM missions could be a luxury reserved for the wealthy segment of population, whereas in other scenarios UAM is one of the cornerstones of the multimodal transport system and an integral component of MaaS. The diversity of possible use cases for UAM and drones will depend on various factor, mostly unrelated to successful technological development.

3. The degree to which **supersonic, hypersonic and suborbital flight** will become part of the aviation landscape within the 2050 timeframe is not yet clear. To enable these developments, there will need to be

developments in vehicle types and related propulsion systems, and in materials to cope with the extreme environments in which the aircraft will operate. Societal acceptance will be a determining factor, given the noise and emissions usually associated with this type of aircraft. There will also need to be developments in systems that ensure the cabin environment is not too unpleasant, for example by ensuring that acceleration loads are not transferred to the passengers.

4. The transition to a true **sustainable aviation** will depend on factors beyond the related technological challenges. Already the implementation of the current sustainable goals within aviation, regarding emissions and noise, will depend on the resilience of the sector in the recovery following the COVID-19 pandemic. A sustainable aviation will also mean different outcomes depending on what sustainability aspects will be perceived as important by society and governments in each scenario. Aspects connected to sustainability in aviation which require balancing are:
   - environmental impacts through the full life-cycle of assets against economic factors;
   - social impacts, such as noise and visual disturbance, against technological possibilities and economic factors;
   - perceptions concerning safety, security and health threats against actual risks and enforcement of excessive regulations. In any case, aviation's transition to sustainability will need inclusive collaborative involvement of citizens in research, through mechanisms such as living labs and co-creation spaces.

5. Given that the level of funding and focus varies between scenarios, the development and access to **research infrastructures** are not guaranteed. Those include, among others, simulation tools, ground and airborne test-benches and rigs, flying test-beds, digital and flying wind tunnels. The breadth of the research infrastructure needed will depend on how the world develops. The current needs for this infrastructure have been assessed and catalogued by the RINGO project[13].

Non-aviation Key Enablers

A number of supporting capabilities from non-aviation sectors emerged as necessary to complement the aviation-specific research efforts in its priority areas.

The impact of the COVID-19 pandemic illustrates aviation's vulnerability to health threats and the need for society-wide, global and overarching **health-care** solutions. This not only applies to the spreading of viruses and bacteria, but also to other health considerations that are specifically associated with flying. Health themes specific to flying that need consideration include:

- fatigue and sleep-related disorders;
- wellness and mindfulness, especially if:
  - flights are long, during which adverse impacts of the cabin atmosphere and environment might accumulate and long periods of inactivity increase the risk of deep vein thrombosis;
  - flights ae potentially physically or mentally stressful with high g-forces and turbulence, especially if they are hypersonic or suborbital.
- the impacts of cosmic radiation on cabin crew and frequent travellers, especially for high altitude flights;
- illnesses and disorders related to long-term exposures to noise.

Many of the technological solutions presented in the study, especially relating to autonomy, are based on a wider use of digital processes, more particularly on AI, machine and deep learning. **Digitalisation** and data science, including big data and data continuity, will provide the backbone for all topics of research in aeronautics. There will need to be extensive mathematics and neuroscience research into these topics.

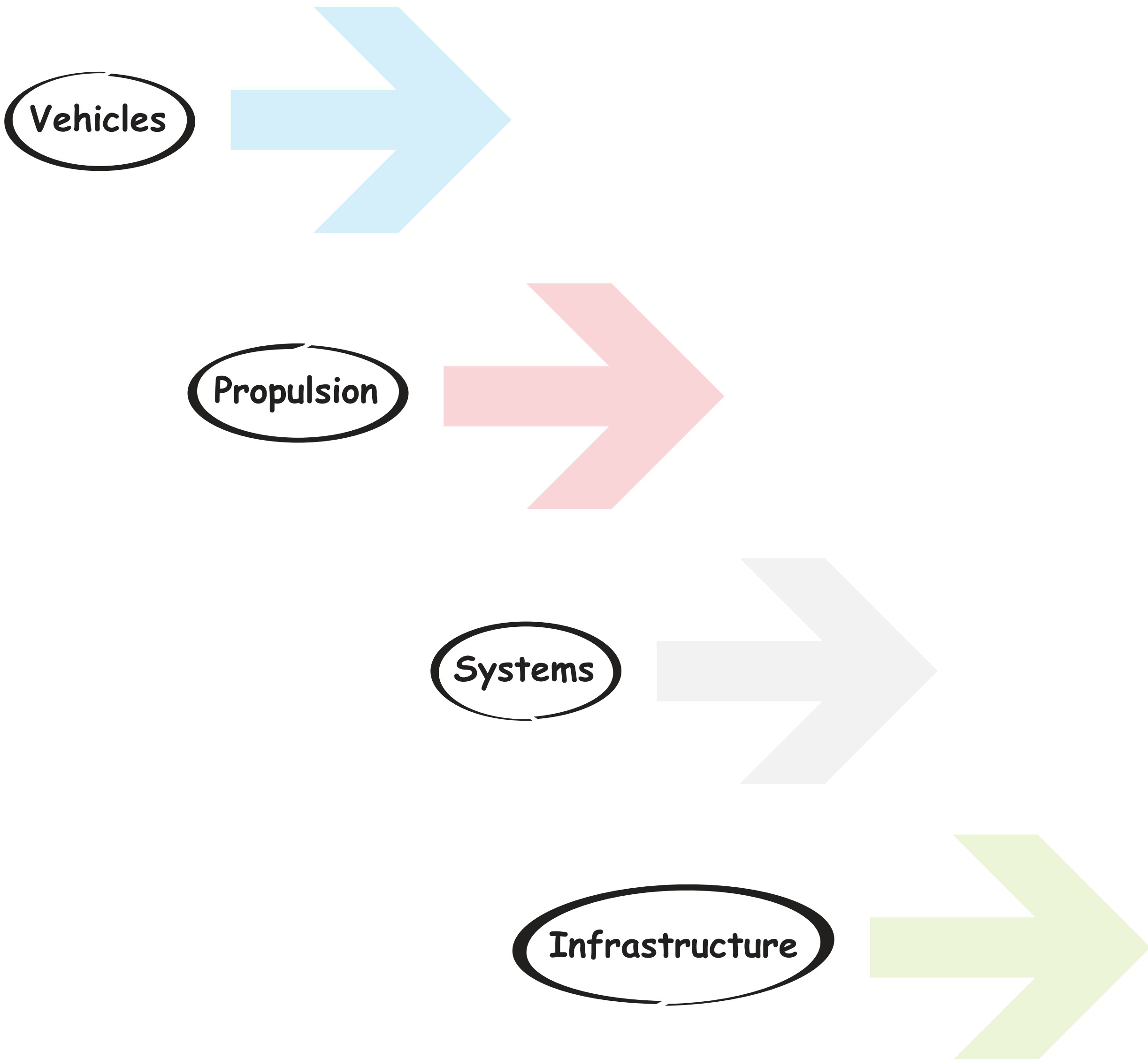
This research will need to also assess the supporting test, validation and certification techniques and processes. **Ethical questions** on the use of AI and harvesting large amounts of, sometimes personal, data will also need to be addressed. Other areas where key supporting capabilities are needed include:

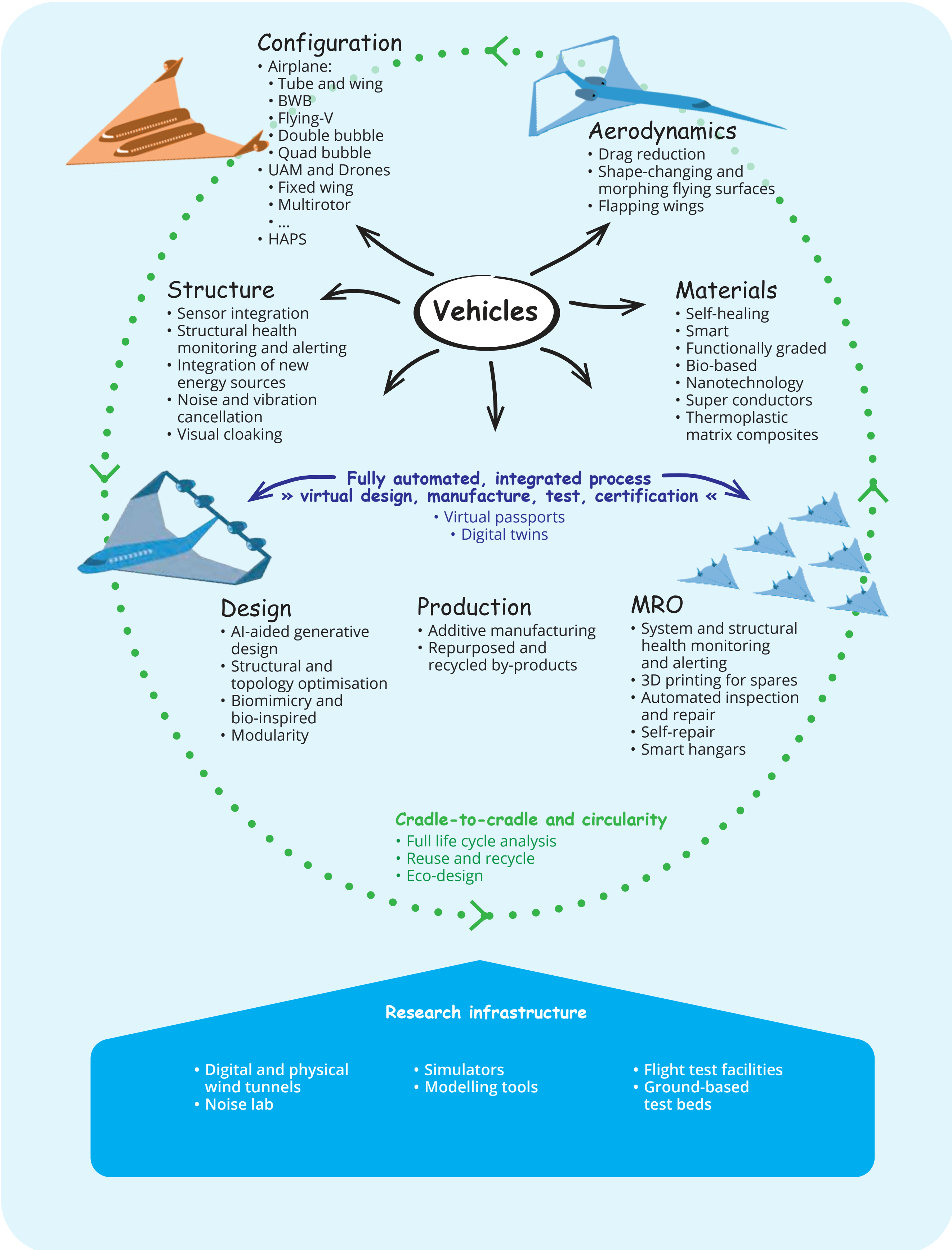
- high performance computing;
- high speed connectivity;
- big data.

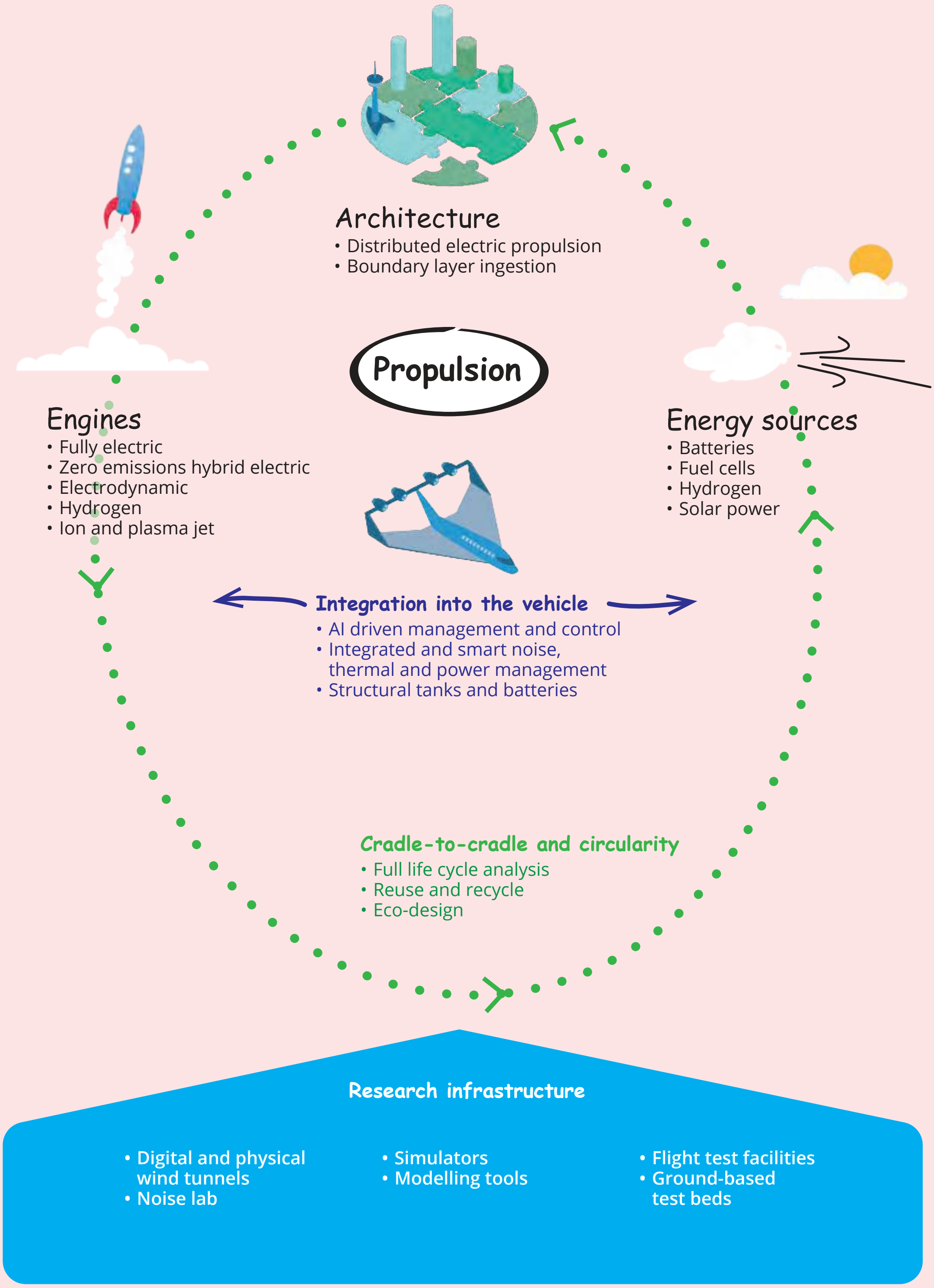
[13] *RINGO. Identification of Aviation Research Infrastructure, Needs, Gaps and Overlaps, EU Coordination and Support Action H2020, March 2017 – February 2020*

Summary of research topics

This section summarises the research topics arising from the scenarios in the main themes: vehicles, propulsion, systems and operational infrastructure. Each theme is divided into the appropriate sub-categories. The capabilities and facilities needed to support the research, in terms of research infrastructure, and underlying technologies are identified. The principal of these capabilities is digitalisation, comprising high performance computing, superfast communications, AI and big data analytics.



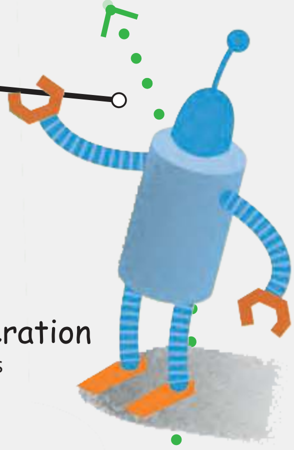

Configuration
• Airplane:
• Tube and wing
• BWB
• Flying-V
• Double bubble
• Quad bubble
• UAM and Drones
• Fixed wing
• Multirotor
• ...
• HAPS
Aerodynamics
• Drag reduction
• Shape-changing and morphing flying surfaces
• Flapping wings
Structure
• Sensor integration
• Structural health monitoring and alerting
• Integration of new energy sources
• Noise and vibration cancellation
• Visual cloaking
Vehicles
Materials
• Self-healing
• Smart
• Functionally graded
• Bio-based
• Nanotechnology
• Super conductors
• Thermoplastic matrix composites
Fully automated, integrated process
» virtual design, manufacture, test, certification «
• Virtual passports
• Digital twins
Design
• AI-aided generative design
• Structural and topology optimisation
• Biomimicry and bio-inspired
• Modularity
Production
• Additive manufacturing
• Repurposed and recycled by-products
MRO
• System and structural health monitoring and alerting
• 3D printing for spares
• Automated inspection and repair
• Self-repair
• Smart hangars
Cradle-to-cradle and circularity
• Full life cycle analysis
• Reuse and recycle
• Eco-design
Research infrastructure
• Digital and physical wind tunnels
• Noise lab
• Simulators
• Modelling tools
• Flight test facilities
• Ground-based test beds


Propulsion
Architecture
• Distributed electric propulsion
• Boundary layer ingestion
Engines
• Fully electric
• Zero emissions hybrid electric
• Electrodynamic
• Hydrogen
• Ion and plasma jet
Energy sources
• Batteries
• Fuel cells
• Hydrogen
• Solar power
Integration into the vehicle
• AI driven management and control
• Integrated and smart noise, thermal and power management
• Structural tanks and batteries
Cradle-to-cradle and circularity
• Full life cycle analysis
• Reuse and recycle
• Eco-design
Research infrastructure
• Digital and physical wind tunnels
• Noise lab
• Simulators
• Modelling tools
• Flight test facilities
• Ground-based test beds

Purposes
- Safety risk assessment and mitigation
- Weather prediction and climate assessment
- Security
  - Threat prediction
  - Surveillance
  - Behaviour monitoring and alerting
  - Decision support
  - Encryption, blockchain
- U-space management

Cabin environment
- High speed connectivity
- Personal entertainment based on immersive technologies
- Vibration and motion control
- Noise cancelling
- In-flight health monitoring
- Automated cabin service

Systems

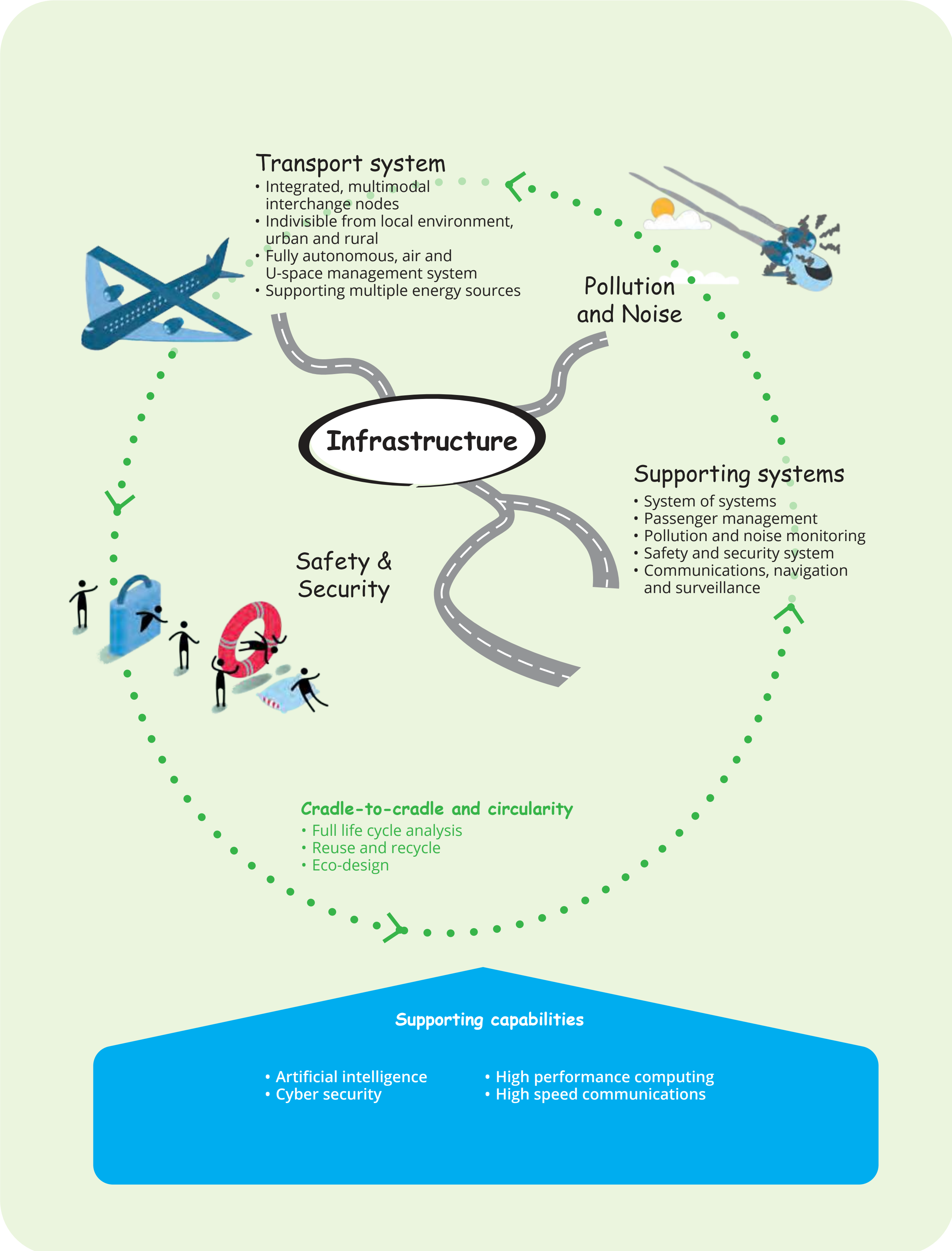


Aircraft on-board systems
- 4-D navigation
- Situational awareness
- Self-separation, collision avoidance and alerting
- Flight control
- Decision support for crewed flights
- Autonomy
- Integrated and smart thermal and power management

Transport system operation
- Passenger information systems
- Planning, management and operation of multimodal transport system
- Flight planning and dynamic replanning
- Fleet planning and management

Cradle-to-cradle and circularity
- Full life cycle analysis
- Reuse and recycle
- Eco-design

Supporting capabilities
- Artificial intelligence
- Machine learning
- Deep learning
- High performance computing
- High speed communications
- Cyber security
- Robotics


Transport system
• Integrated, multimodal interchange nodes
• Indivisible from local environment, urban and rural
• Fully autonomous, air and U-space management system
• Supporting multiple energy sources
Pollution and Noise
Infrastructure
Supporting systems
• System of systems
• Passenger management
• Pollution and noise monitoring
• Safety and security system
• Communications, navigation and surveillance
Safety & Security
Cradle-to-cradle and circularity
• Full life cycle analysis
• Reuse and recycle
• Eco-design
Supporting capabilities
• Artificial intelligence
• Cyber security
• High performance computing
• High speed communications

Abbreviations

3D	Three-Dimensional
4D	Four-Dimensional
ACARE	Advisory Council for Aviation Research and Innovation in Europe
AI	Artificial Intelligence
ANSP	Air Navigation Service Provider
ATM	Air Traffic Management
ATS	Air Traffic Services
BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
CROR	Counter Rotating Open Rotor
CTOL	Conventional Take-Off and Landing
DEP	Distributed Electric Propulsion
EASN	European Aeronautics Science Network
eCTOL	Electric Conventional Take-Off and Landing
EREA	Association of European Research Establishments in Aeronautics
eVTOL	Electric Vertical Take-Off and Landing
FANET	Flying Ad-hoc Network
GEV	Ground Effect Vehicle
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAPS	High Altitude Platform System
HEP	Hybrid Electric Propulsion
ICT	Information and Communication Technology
ITPM	Integrated and Smart Thermal and Power Management
KPI	Key Performance Indicator
LNG	Liquified Natural Gas
MaaS	Mobility as a Service
MRO	Maintenance, Repair and Overhaul
OEM	Original Equipment Manufacturer
PTL	Power to Liquid
R&D	Research and Development
SAF	Sustainable Alternative Fuel
SDG	Sustainable Development Goal
SESAR	Single European Sky ATM Research
SHM	Structural Health Monitoring
SRIA	Strategic Research and Innovation Agenda
STOL	Short Take-Off and Landing
STOVL	Short Take-Off and Vertical Landing
SWIM	System Wide Information Management
TCT	Tail Cone Thruster
TRL	Technology Readiness Level
UAM	Urban Air Mobility
UAS	Uncrewed Aerial System
UAV	Uncrewed Air Vehicle
UHTCC	Ultra-High Temperature Ceramic Composite
UN	United Nations
VTOL	Vertical Take-Off and Landing

Colophon

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