PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

PARE

CHAPTER 8

Emerging Aviation Technologies

Final Report

WWW.PAREPROJECT.EU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 769220. This publication [communication] reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Table of Contents

List of Figures

List of Tables

Chapter 8 – Emerging Aviation Technologies

Aeronautics is a leader in the introduction of new technologies in many sectors, with 'spin-offs' to other industries, both transport (cars, ships, trains) and consumer (electronics, services, etc.). The aerodynamic shapes, strong and lightweight structures and other technologies pioneered in aeronautics find applications in cars, high-speed trains and other vehicles. Aeronautics was the pioneer in anti-skid braking systems (ABS) and head-up displays (HUDs) long before their use in cars. The first microcircuits appeared in rugged, light and small computers in ballistic missiles at a time when similar computing power required a large air-conditioned room. The example of microelectronics shows how the widespread adoption of a technology turned aeronautics into a relatively small user-facing obsolescence issue. Satellite navigation demonstrates the special needs of aeronautics compared with a wide range of other users. The inverse process of 'spin-in' from other sectors into aeronautics is as important as the direct process of 'spin-off'; specific technologies developed in other sectors can contribute to sustaining the relentless progress in aeronautics, which is the main driver for the renewal of aircraft fleets. For example, the capital investment in a new airliner can only be recovered if there is a gain efficiency of at least 10% relative to a preceding generation; in other sectors of aeronautics gains in various measures of performance, new capabilities and improved availability and operability are decisive factors for fleet renewal.

8.1 Electric propulsion and electrified airplane components

The electrification of airplanes takes place on two levels. The main level is focussed on the development of full-electric airplanes (8.1.1.) with the aim to lower emissions and to reduce flight noise as well as to reduce flight costs, which are mainly determined by the cost of jet fuels which have been historically mostly increasing. The second level is related to electrified airplane components, which replace conventional mechanical, hydraulic, and pneumatic airplane systems which lead to reduced weight, higher reliability, lower maintenance costs and increased efficiency and therefore lower emissions as well.

The energy density of electrochemical power sources - ECPS (batteries and fuel cells), however, is for the time being not high enough (8.1.4) for flight ranges comparable with the conventional propulsion. Therefore, the development of electrical airplanes is currently concentrated on light aircraft and short-range.

To increase the flight range fuel cells are used as ECPS because a doubling of the energy leads not to a doubling of the FC mass as with batteries but much less (8.1.1.1.3).

Furthermore, to increase flight range solar-powered aircraft are used, where the PV modules produce during the flight additional energy to the energy of the battery (8.1.1.1.4).

Additional energy can be produced also by conventional turbine-generators (8.1.2). This turbine-generators/electrical power sources hybrid-electric propulsion is for the time being the preferred way for flight ranges of up to 1000 km and > 10 passengers.

Because also the mass of the aircraft determines the flight range all component of the plane have to be weight-optimized, particularly the electric motors (8.1.5).

8.1.1 All electric propulsion

8.1.1.1.Battery and fuel cells powered air vehicles

FLIGHT DISTANCES

The flight range (R) of all-electric aircraft is determined by:

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{ECPS}}{m} \qquad (1)$$

E^* - Specific electrical energy of electrochemical power sources – ECPS (batteries, fuel cells) [Wh/kg]
η_{total} - System efficiency from ECPS to propulsive power
L/D - Lift over drag ratio; depends on aircraft design
m_{ECPS} - Mass of ECPS
m - Airplane mass (m_{empty} + $m_{payload}$ + m_{ECPS})
m_{ECPS}/m - ECPS mass fraction
g - Gravity acceleration

For battery propelled airplanes is based on the above equation the range - R (km) shown in Figure for different specific energies - E^* (Wh/kg) of batteries ECPS, for constant η_{total} = 0,75, for different L/D values (40 - glider, 10 - passenger aircraft) and different ECPS mass fraction $m_{batt}/m_{airplane}$, with today practically realistic values of 0.1 – 0.4.

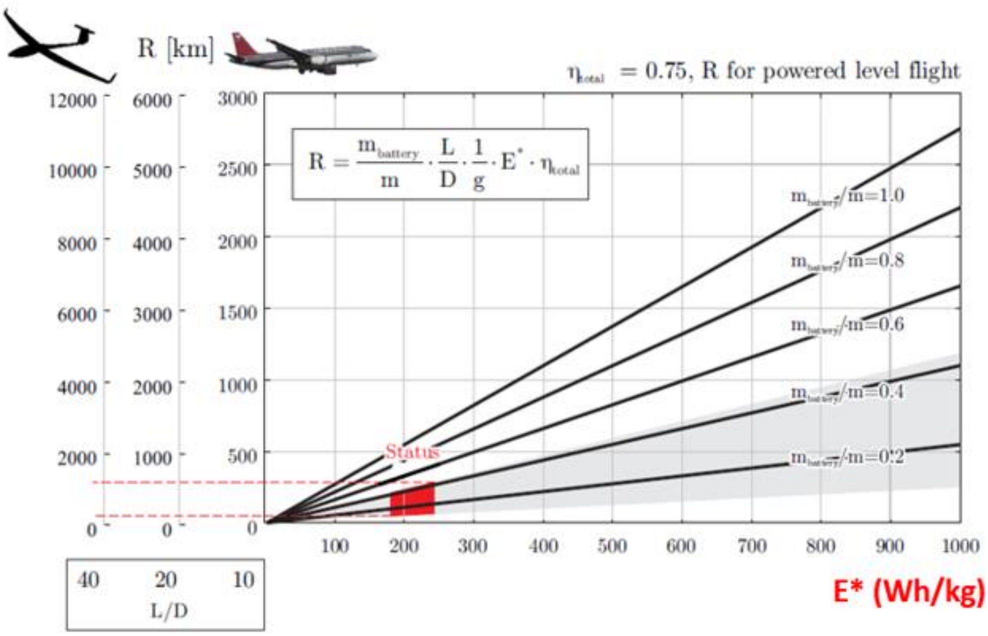


Figure 8.1: Airplane range (R in km) vs. specific energy of the battery (E*) for η_{total} = 0,75; different L/D values and different battery mass fraction $m_{batt}/m_{airplan}$ [ii]

In the red area in the low left corner of Figure the status quo is shown.

For a general aviation aircraft with L/D ≈ 10, $m_{ECPS}/m \approx 0.2 \ldots 0.4$, $\eta \approx 75\ \%$ and specific ECPS energies of 250 Wh/kg a range of about 250 km is possible[ii]. Flight ranges of ≥ 1000 km are reachable in particular only via an aircraft design with L/D ≥ 20 and ECPS with ≥ 400 Wh/kg. As ECPS could be used batteries and fuel cells – see 0.

High flight ranges are possible also with fuel cells as ECPS, because their energy is determined mainly by the hydrogen, i.e., long flights are possible by increasing the hydrogen mass, which contributes only insignificantly to the total airplane mass – see 0.

In general, larger flight ranges could be possible by

- By higher specific battery energy - see section 0
- By use of hydrogen fuel cells - see section 0
- By battery charging during the flight with PV – see section 0
- By battery charging during the flight with a kerosene gas turbine (hybrid) – see section 0
- By better plane design: larger L/D and/or battery mass fractions

ALL-ELECTRIC AIR VEHICLES POWERED BY BATTERIES

Airplanes

Short-range aircraft

Caused by the limited specific energy of the today ECPS the development of electric aircraft is concentrated on applications with low total weight, i.e. small passenger numbers and/or low payload as well as limited endurance and speed. These limitations are acceptable for air taxis, general aviation and recreational aircraft, and regional and business aircraft, and drones transporting measuring sensors[iii].

Application areas are *Commuting and Traveling* (Urban Air Taxi, Intercity Air Express, Airport Shuttle, Personal Air Vehicle, Ferry Substitute, Flying Mountain Express, Aerial Desert Vehicle, etc), *Surveillance and Safety* (Flying Ambulance, Aerial Police Patrol, Aerial Border Reinforcement Patrol, Flying Fire Brigade, Flying Sea / Mountain Rescue Mission Vehicle, etc.), *Working* (Flying Company Car, Flying Warehouse Vehicle, Flying Post Vehicle, Aerial Construction Vehicle, Flying Research Vehicle, e.g. Animals, Ocean, Glacier, Pole; etc.), as well as *Leisure and Recreation* (Aerial Amusement Park Vehicle, Aerial Vehicle for Professional Air Races, Aerial Sightseeing Vehicle, Flying Shuttle, etc.)[iv].

Totally more than 130 electric VTOL concepts have been proposed[v] and venture capitalists have invested more than 1 billion dollars into promising eVTOL startups[vi]. Information about the eVTOL developments are given at eVTOL NEWS[vii]

Besides the VTOL concepts also short take-off/landing technologies are under development[iv] (see Figure).

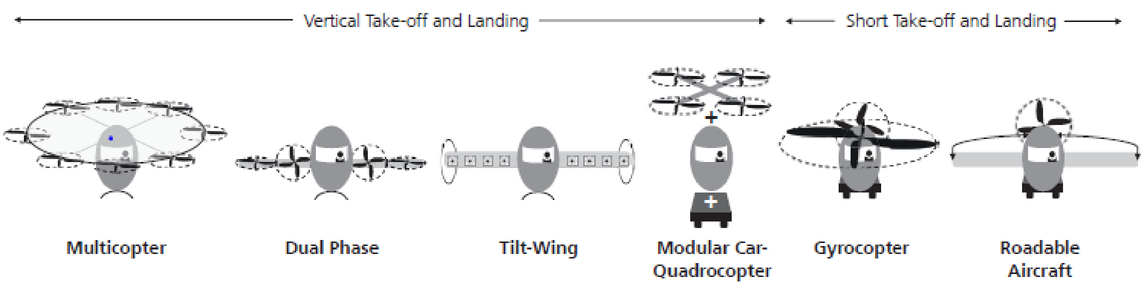


Figure 8.2: Different airplane technologies for 3D trafficiv

Data on the planes and ECPSs of the in the following mentioned aircraft are to find at the relevant literature references.

Multicopter / Multirotor

This concept features multiple motors and propellers around a cabin to create thrust in a vertical direction. Compared to other concepts, they still have significant efficiency disadvantages, therefore this concept is designed for short-range use.

Enterprises as Volocopter 2X (Germany)[viii] and E-Hang 184 (China)[ix] testing already under real-life conditions. A special development is the Airspeeder Mk4 of the Australian company Alauda. This aircraft is under development for air-racing like Formula One for cars[x].

A general view on the Volocopters 2X and the Volocopter VoloDrone shows the next Figure.

Figure 8.3: First flight of the multirotor Volocopter 2X in Singapore and Volocopter VoloDrone (Germany) xi

Dual-Phase

Propellers mounted to wings create vertical thrust during take-off and landing; another propeller mounted to the tail creates horizontal thrust with higher efficiency. Therefore, this concept is related to longer distances. Examples are the Cora of the US company Wisk (formerly Kitty Hawk Corp.)[xii], the Pegasus PAV of the US company Aurora Flight Sciences[xiii].

Figure 8.4: The dual-phase Cora of Wisk (USA)xii

Tilt-Wing / Tilt-Rotor / Tilt-Duct

This technology allows to tilt wings, rotors or ducts and so redirect the thrust from a vertical direction (take-off and landing) to a horizontal direction (cruise); the latter with higher efficiency and therefore for longer distances flights. The main difference between eVTOLs in this category is whether they have fans or propeller. The developers are the German company Lilium [xiv], the US company Aurora Flight Sciences with the Aurora XV-24 LightningStrike[xv], the US company Joby aviation with the S2 VTOL [xvi], and since 2020 the US aerospace company Archer[xvii].

Figure 8.5: Tilt duct Lilium jet (Germany)xiv

Modular Car-Quadrocopter

A capsule for the passenger can be mounted (autonomously) either on a fully electric car platform for ground transportation or on a fully electric multirotor module for air transportation. Audi and Airbus have developed this concept so-called Pop.Up Next[xviii] which has recently been discontinued.

Figure 8.6: Modular Car-Quadrocopter of Audi and Airbus (Germany)xviii

Gyrocopter

The gyrocopter has an active propeller creating horizontal thrust and a passive rotor creating a vertical thrust through the airflow at the top which is also called autorotation.

This conceptual approach is followed by the Germany company AutoGyro GmbH (eCavalon)[xix] and the Netherland Company PAL-V[xx] (still with conventional engine).

Figure 8.7: Gyrocopter eCavalon of AutoGyro GmbH (Germany)xix

Roadable Aircraft

A Roadable Aircraft is a car which has the ability also to fly by using (foldable) wings.
The Chinese-US company Terrafugia has been prototyping and testing the hybridized model TF-X[xxi].

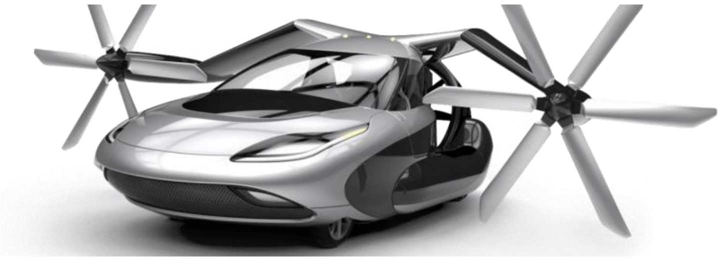


Figure 8.8: Roadable aircraft TF-X of Chinese-US company Terrafugiaxxi

Conventional E-Aircraft

This group of e-planes are based on conventional commercial aircraft by replacing the internal combustion engine and kerosene tanks with the electric motor and battery.
The first electric plane was the MB-E1 based on the fully certified motor glider HB-3 with minor modifications to carry batteries (100 V, 24 Ah NiCd batteries by VARTA) and electric motor (10 kW by BOSCH) build by the Austrian manufacturer H. Brditschka in 1973 – see Figure. The max. fly time of MB-E1 was only about 10 min

Figure 8.9: First electric plane MB-E1xxii

A newer development by the Canadian commuter airline Harbour Air with the US propulsion company MagniX is the seaplane eBeaver a modified version of the six-passenger de Havilland's legendary DCH-2 Beaver. Instead of a 330 kW radial piston engine or turbine, the eBeaver is powered by a Magni500 electric motor capable of generating as much as 560 kW, driven by Li-batteries. The first fly for 10 min was 2019; Harbour Air expects the eBeaver to go into commercial service in 2022.

A full electrical Cessna Grand Caravan 208B with 4 passengers, was developed also by the US companies MagniX and AeroTEC and it is expected the aircraft to be registered in 2021. The flight range with then 12 passengers will be 160 km with the statutory reserves included. Batteries are state-of-the-art LIBs. The first flight was in May 2020.

Other classifications by the thrust type are given e.g. by eVTOL News[vii]: Vectored Thrust, Lift + Cruise, Wingless (Multicopter), Hover Bikes & Personal Flying Devices, Electric Helicopters.

The strongest development takes place at VTOL taxis normally with a range between 50…100 km and partially larger, as by Lilium Jet (300 km). Other developers are Rolls-Royce, Even Aston Martin, Vertical Aerospace, Karem Aircraft, SAMAD aerospace and Urban Aeronautics.

Medium range aircraft

Under development are also regional and business (about 10 people) aircraft with targets of >500 km, e.g. EasyJet developments with Wright Electric (US), magniX and AeroTEC (US) - Cessna Grand Caravan 208B, or Eviation (Israel) - ALICE plane.

The first flight of full electrical Cessna Grand Caravan 208B with 4 passengers was in May 2020. The electrical Cessna is developed by the US companies magniX and AeroTEC and it is expected the aircraft to be registered in 2021. The flight range with then 12 passengers will be 160 km with the statutory reserves included. Batteries are state-of-the-art LIBs.

The ALICE plane is a 9+2-seater, with an ultra-light all-composite airframe, an exceptional battery mass fraction of 0.65, and a battery consists of 900 kWh Li-ion battery and a primary Al-air system (as IFR reserve) which gives together an extreme high specific energy of 400 Wh/kg. First flights were already done, a pilot production should start in 2021. Unfortunately, in January 2020 the ALICE Aircraft experienced a fire incident caused by a ground-based battery system.

Figure 8.10: Model of the all-electric airplane ALICExxiii

Examples for general aviation and recreational aircraft are pilot training aircraft which belongs to the eCTOL (electric conventional takeoff and landing) category. The producer is Slovenian Pipistrel - Virus SW 128; Chinese Liaoning Ruixiang - RX1E-A; two-seaters, flight time 1-2 h, price about $150,000.
Furthermore, are to mention also the eFlyer 2 (2 persons) and the eFlyers 4 (4 persons) of the US company Bye Aerospace[xxiv]. The eFlyers are selling well: Quantum Air plans to launch the world's first commercial electric urban air mobility (UAM) network 2021 around Los Angeles with a fleet of 22 eFlyers. The Norwegian company OSM Aviation ordered 60 eFlyers to use for training in its flight training centres.

Figure 8.11: eFlyers 2 of the US company Bye Aerospacexxv

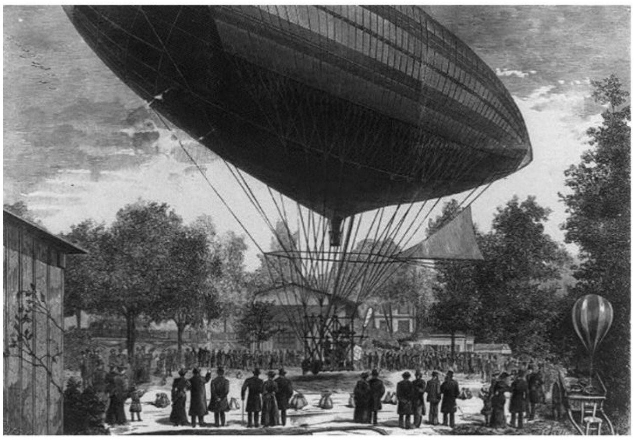
Bye Aerospace is cooperating with the UK battery manufacturer OXIS, who is developing Li-S cells which have a specific energy of 400 Wh/kg[xxvi].

Larger range

Larger commercial aircraft which could compete with the smaller members of the A320 and 737 families are developed by Airbus, Boeing, and Wright Electric with a time target of commercialization of 10 – 20 years[iii].

Airships

Besides planes occasionally also airships are electrified. Historically the first flying vehicle with electricity support was 1883 the airship of the French aviator A. Tissandier with 24 chromic acid cells (Zn-Graphite with potassium bichromate and sulfuric acid as electrolyte-depolarizer) and a 4 kW Siemens electromotor.



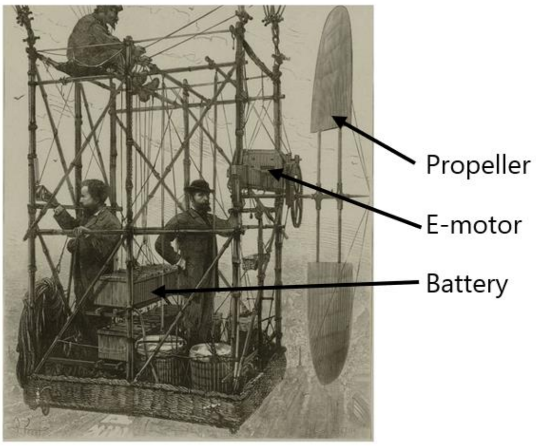


Figure 8.12: First electrified airship of A. Tissandierxxvii

One year later the battery powered La France was introduced by A. Krebs and Ch. Renard, both French military officers. La France was the first fully controlled airship which was able to return to its starting point in largely good weather conditions.

The British company Hybrid Air Vehicles (HAV) has developed since about 2010 at first for the US Department of Defence the airship HAV 304 (first flight August 2012) and later in the UK also for civil applications the very similar Airlander 10 (first flight August 2016). Airlaner 10 specifications are 5 days airborne, 10 t payload, 7,500 km range, 6 km travel altitude. The propulsion was first based only on four V8 diesel engines with 250 kW each. Now hybrid-electric configurations (two diesel engines, two electric motors) and also an all-electric project (E-HAV1) is under development with 500 kW electric propulsion.

Figure 8.13: Airship Airlander – 10xxviii

FUEL CELL-POWERED AIRCRAFT

Fuel cell driven airplanes give the possibility for longer flight ranges, caused by the relatively low weight of the hydrogen tank which determines the energy of the fuel cell system. Usually, 500 – 1000 Wh/kg are reachable with FC systems and H2 tanks, which fit the plane; see section 0.

For the time being, hydrogen is used in the pressurized form (300 – 700 bar) for smaller PEMFC aircraft. For larger airplanes liquid hydrogen is preferred by its higher energy density (liquid: 2.4 kWh/L; 700 bar: 1.3 kWh/L, 300 bar: 0.8 kWh/L). The energy density of both liquid and pressurized hydrogen is much lower as kerosene (9.7 kWh/L). The energy density differences continue to increase caused by the higher mass of the H2 tanks. But the specific energy of hydrogen (33 kWh/kg) is higher as kerosene (12 kWh/kg). So, the high hydrogen volume must be managed by design, but the low hydrogen weight increases the flight range. Concerning batteries, the total weight of the airplane is reducing with increasing flight time by consumption of hydrogen. For long-range passenger airplanes liquid hydrogen will be probably caused by the lower volume the only options for hydrogen storage although the liquefaction of hydrogen needs more energy as to pressurize hydrogen. A NASA project focuses on the development of a fully electric aircraft platform that uses cryogenic liquid hydrogen as an energy storage method. But even the use of liquid hydrogen leads to significantly extended fuselages for LH2 storage which consume more energy than conventional aircraft.

A general overview of main technical, environmental, and economical data of commuter and regional aircraft is given in Figure.

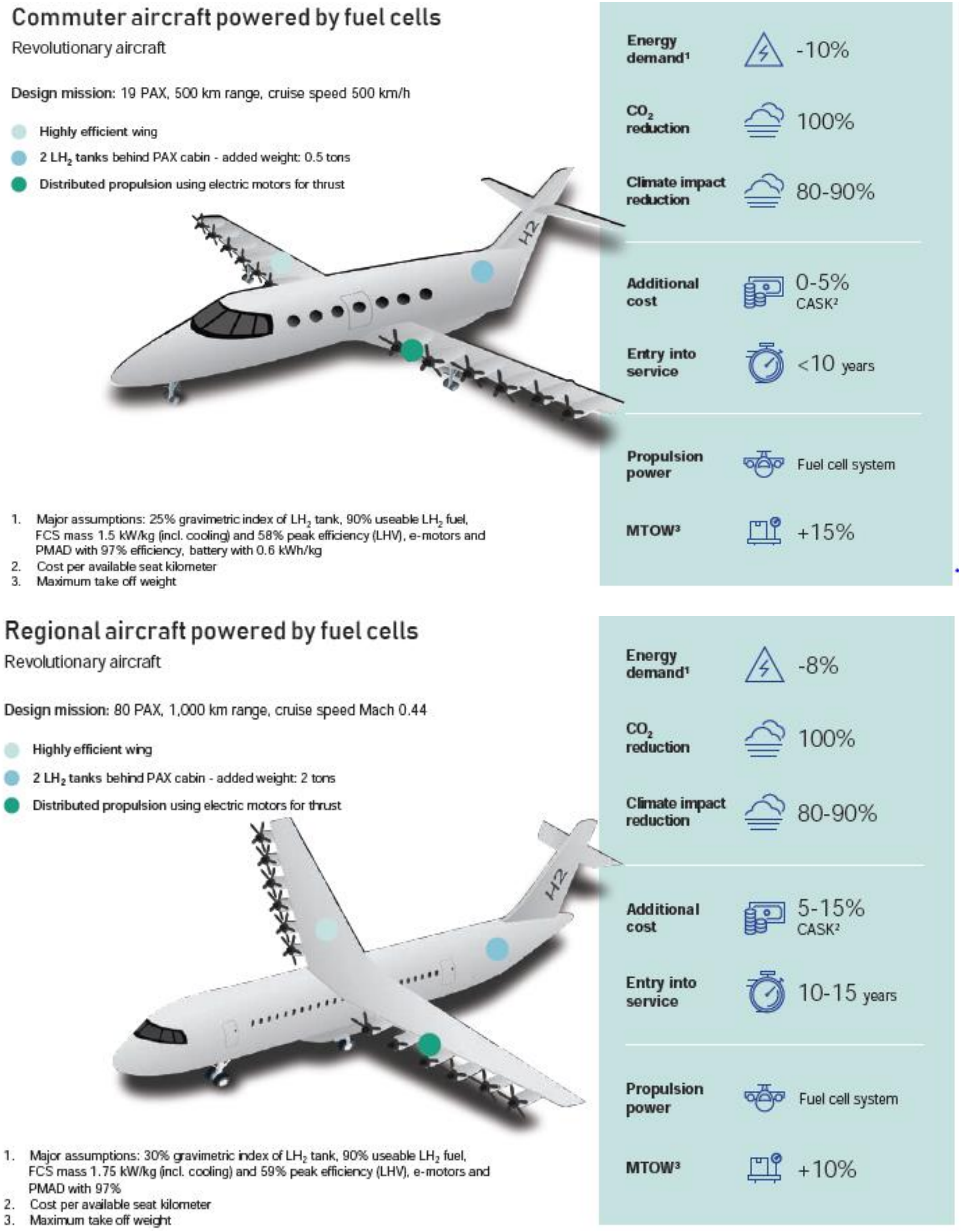


Figure 8.14: Important technical, environmental, and economical data tech parameter of commuter and regional aircraft-based on PEM-Fuel Cellsxxxiv

It is for the proton exchange membrane fuel cell (PEMFC) use in airplanes to consider that the operating conditions of PEMFCs in the air are caused by changing altitudes with changing air pressures and temperatures more demanding as terrestrial applications.

In 2008 Boeing Research & Technology Europe (BR&TE) tested a civilian 2-seat Diamond Aircraft Industries DA20 (called Theator Airplane) running on a PEMFC (UK Intelligent Energy) and Li-ion battery.
A further development was 2009 the Antares DLR-H2 plane based on the Antares 20E aircraft of Lange Aviation driven only by a 25 kW PEMFC (hydrogenics) with 44 % efficiency. In 2010 in the framework of the EU "ENFICA-FC" project (Environmentally Friendly Inter City Aircraft powered by Fuel Cells) a two-seater all-electric aircraft was developed driven by a PEMFC (20 kW)/Li-Ion battery (20 kWh) hybrid system with 350 bar hydrogen storage. Based

on the Antares experiences the HY4 all-electric plane the DLR developed in 2016 a four-seater powered by a PEMFC/Li-ion battery hybrid system. HY4 technical data: weight - 1,500 kg; e-motor - 80 kW; max./cruising speed - 200/145 km/h, range - 750 – 1500 km, PEMFC - 45 kW; 100 kg; H_2 – 9 kg, 437 bar, 170 kg; LCO battery - 21 kWh, 130 kg. With liquid hydrogen ranges of > 2,000 km would be possible. Studies for a 6 and also a 40 seat PEMFC/Li-Ion hybrid-powered all-electric aircraft are done also by the DLR Stuttgart.

Other examples are Furthermore PEMFCs together with Li-ion batteries are demonstrated to power small unmanned aerial vehicles UAVs (drones) for ≥ 10 h[xxix] . E.g. the Ion Hybrid Tiger of the US NRL, a long-endurance solar – LIB – PEMFC (625 W) soaring UAV has a flight time of 26 h with 350 bar H_2 and with liquid H_2 48 h.[xxx].

Das US-Startup Alaka'i Technologies is developing an air-taxi called Skai based on PEMFCs and hydrogen tanks with 200 and 400 litres pressurized hydrogen, 400 l will enable the aircraft to stay afloat for up to four hours or travel for 650 km without refuelling. Three 100 kW PEMFCs power six electric motors. This leads to a top speed of up to 190 km/h. At a speed of 137 km/h, however, the efficiency and therefore also the range are increasing[xxxi].

Figure 8.15: Skai Model driven by hydrogen FCsxxxi

Ballard Power Systems, Inc. founded the subsidiary Ballard Unmanned Systems, Inc., which has launched 2019 the FCair fuel cell product line for smaller commercial UAVs[xxxii]. The FCair system includes the H2 PEMFC, the H2-tank, pressure regulators, refuelling solutions and hydrogen gas supply. The FCair will be produced as FCair-600 (600 W) and FCair-1200 (1,200 W) unit with a built-in hybrid battery control and charging. The system is using a lightweight Carbon Overwrapped Pressure Vessels (COPVs) with about 400 bar H2-pressure. Ballard quantifies the advantage of the FCair systems in UAV applications: 3x the flight duration of batteries; 5x the reliability and a fraction of the noise of small internal combustion engines.

It is to notice that hydrogen is used for aircraft besides fuel cells also as fuel for turbines instead of kerosene in larger airplanes. Prototypes for hydrogen combustion aircraft are the Tupolev TU 155 (1989), and the Boeing UAV Phantom Eye (2010). But they are not electric aircraft and because of other issues, the development was discontinued. The drawbacks were NO_x, noise, and larger production of water vapour (based on H_2 fuel and not C_xH_y) which has a larger lifetime at higher altitudes[xxxiii]. Water vapour is known to be Earth's most abundant greenhouse gas. The EU, however, has taken up 2020 the topic again and published a study[xxxiv] that estimates that H2 combustion aircraft could reduce climate impact in flight by 50 to 75 % (fuel-cell propulsion by 75 to 90 %; synfuel propulsion by 30 to 60 %). Several technological unlocks need to happen: enhancing the overall efficiency with lighter tanks (targeting 12 kWh/kg), liquid hydrogen (LH2) distribution within the aircraft, turbines capable of burning hydrogen with low-NOx emissions, and the development of efficient refuelling technologies enabling flow rates comparable to kerosene need to be developed. Industry experts project these important advancements are possible within five to ten years. Also, for short-range aircraft, a hybrid propulsion approach (H2 combustion and fuel cell) is discussed.

For more about hydrogen turbine aircraft, please see chapter 19 (Sustainable fuels for the new Green Deal), section 5 (New propulsion technologies: Liquid Hydrogen).

SOLAR-POWERED AIRCRAFT

Solar-powered aircraft (SPA) are solar generator/ECPS hybrids, which should eliminate the current disadvantage of all-electric aircraft, i.e. the limited range caused by the too low specific battery energy. Furthermore, they offer the ultimate promise of environmentally clean operation for long periods up to a month or even years.

Solar panels are the electricity generator to power the electric motor of the aircraft and to charge the battery for night flights. With about max. 250 W/m^2 PV panel for 50 kW electricity a wing area of at least 200 m^2 panel area have to covered with solar panels. It is, however, to take into account that the radiation increases with higher altitude.

One main future application is the use of UAV solar-powered aircraft acting as a transmission or relay station over a limited geographical area as a much cheaper alternative to geostationary satellites in about 36,000 km altitude with costs of about $400-500 mill. These high-altitude pseudo satellites (HAPS) fly above cloud cover at an altitude of about 20 km. Caused by the limited power available typically speeds are up to 100 km/h, which have to keep the SPA permanent on a geostationary position despite strong stratospheric winds. Examples are the Odysseus (Figure 2), developed by the Boeing daughter Aurora Flight Sciences with a wingspan of 74 m and an extremely high payload of 25 kg, which first flight should be in the second quarter 2019. But Aurora twice delayed Odysseus' first flight before delaying it indefinitely.

Figure 8.16: Solar-powered aircraft Odysseus of Aurora Flight Sciences xxxv

The Odysseus can be used also as high-altitude, long-endurance (HALE) UAV. Another HAPS example is the Zephyr of the Airbus partner Qinetiq which flew in 2018 25 days. Zephire S technical data: wingspan 25 m, weight 80 kg, payload 5 kg, Li-ion cells of Amprius with 100 % silicon nanowire anodes and 435 Wh/kg as well as 1200 Wh/litre.

Also round the globe flight or long-time flights by solar-powered aircraft are possible. These solar-powered planes are used either as unmanned platforms for sensors or manned for demonstration and leisure. At the beginning of the 1990s, NASA has developed different solar-powered aircraft as Pathfinder, Pathfinder Plus, Centurion, Helios, and also have developed prototypes - as well as Airbus/Siemens.

The Solar Impuls, developed by the Swiss B. Piccard and A. Borschberg, at beginning of the 2010th was a milestone. The Solar Impulse 2 has had a wingspan of 72 m, 270 m² PV panels and 4 x 41 kWh Li-ion batteries (164 kWh, 633 kg, 260 Wh/kg) ultra-high-energy lithium nickel-manganese-cobalt oxide (NMC) batteries from Kokam. The circumnavigation of the earth with 42,438 km flown took 23.25 days was done in 2015/16 in 17 stages. The longest leg was with 7,212 km and 117 h from Japan to Hawaii

Reaching the operating altitude takes long and requires good weather. But the real-life needs operating under all-weather conditions and round-the-clock operations. The planes will have sophisticated light plane designs (very large wings for high lift values and area for PV modules). A commercial introduction will be probably only > 2035.

8.1.2 Turbine-generator/ electrical power sources hybrid-electric propulsion

Besides PV modules also a generator driven by a kerosene gas turbine could fit a battery-hybrid system. The gas turbine/generator, however, has normally a high CO_2 footprint and is noisy. But the turbine can continuously operate within its ideal speed range, which saves fuel (CO_2) and reduces the noise level. Power higher than the generator for take-off, climb, cruise, and the land is provided by the battery. Therefore, for the aircraft design not only the specific energy (Wh/kg) of the battery is important but also the specific power (W/kg). The battery could be charged on the ground or during the flight by a slightly larger turbine.

Turbine/battery hybrids work mostly as parallel hybrid, the generator powers the electric motors for the rotors. In this way several small electric motors could be used, leading to new forms in aircraft design with improved aerodynamics and efficiency. But the aerodynamic advantages have to overcompensate the weight drawback of hybrid systems.

Besides turbine/battery hybrids there are also internal combustion engine (ICE)/battery hybrids, where both powertrains (ICE, electrical motor) work independently of each other, as e.g. in the twin-engine Ampere 337 (based on Cessna 337) where one engine was replaced with a battery-driven electric-propulsion system – first fly June 2019. Airbus is developing at the same time the 100-seater (!) regional aircraft E-Fan X[xxxvi] based on a BAe 146 in the first step by replacing one of the four engines with a 2 MW electric motor. An alternative to the Airbus/Rolls Royce parallel hybrid is the United Technology DHC-8 series hybrid.

Critical for the hybrid design is the main goal of the application: range, CO2 footprint, or/and cost, which determines the degree of hybridization.

The first flight of a hybrid plane was done 2011 with the two-seater DA36 E-Star power glider (Diamond Aircraft) with a 70 kW electric motor powered via a battery, which was charged during cruising via a 30 kW Wankel engine, i.e. the DA36 is a serial hybrid,

Other developments are from the US company Zunum Aero which plans in cooperation with Boeing and JetBlue a hybrid electric drive system for 9-passenger + 1 pilot, with 550 km/h; first flights will be 2021 and delivery should start in 2022. Zunum Aero claims about $100 million in pre-orders.

The three French aerospace companies Airbus, Daher and Safran are developing a hybrid-electric plane based on the Turboprop-Einmot Daher TBM with the name EcoPulse (5 passengers). The engine drives the main rotor on the fuselage of the aircraft. The electric motors drive six smaller propellers attached to the wings – three on each side; 2022 will be the first flight.

The German start-up e.SAT is developing together with the German MTU the 5 seat Silent Air Taxi which is a hybrid with conventional combustion engines and electric motors. 1000 km range, 300 km/h speed, and a runway of about 400 m are the targets. The first flight will be in 2022

The success of turbine-ICE/battery hybrids depends strongly on the reachable fuel savings, which should be > 30 %. It is predicted that only in the year 2035, hybrid-electric aircraft with about 100 passengers and 1000 km range will be commercialized.

Besides the above shown hybrid technologies, micro hybridization is developed, this is a combination of combustion engines with small, electric motors (like car start-stop systems). E.g. at helicopters at low power cruise one of the two engines could be shut down and at higher power demand (landing, high speed) the engine is restarted by an electric motor.

8.1.3 Turbo-electric propulsion

The principle of the turbo-electric propulsion is already described in section 0 as part of the hybrid system: the kinetic energy of a turboshaft is transformed into electric energy via a generator and an electric motor to drive multiple, distributed fans.

Caused by the low specific energy of lithium-ion batteries it makes sense for long-range high-speed aircraft carrying hundreds of passengers or tens of tons of cargo to use only gas turbines. The main issue then becomes one of transmission of tens of MW in an aircraft from the electric generator to the electric motors distributed over the span of the wing. Tens of megawatts of electrical power translate to currents of thousands of amperes at thousands of volts. The very high voltages require special equipment and can pose challenges of electromagnetic interference and electrical discharges. Very large currents over normal conductors lead to high dissipation by the Joule effect, hence significant power losses; these power losses take the form of heat that is difficult to dissipate in an aircraft. The electric power transmission without electric resistance has been demonstrated by superconductors operating at very low temperatures close to absolute zero. Creating such cryogenic conditions is known for mostly for rockets rather than aircraft. Room temperature superconductors have been demonstrated on a limited scale.

The prospects for an Airbus or Boeing type electric transport aircraft could thus be summarized as:

(i) gas turbine(s) driving electric generator(s) feeding distributed electric propulsion;
(ii) power transmission via superconductors with zero electric resistance and dissipation.

While this is a somewhat distant prospect, progress in the electrification of aircraft will continue, with the attraction of replacing multiple systems (hydraulic, pneumatic, etc.) by a single electric architecture. The installed power of the order of 2 MW in the Boeing 787 and Airbus A350 matches the next Airbus electrical experimental aircraft: a British Aerospace 146 regional jet airliner with one of the four engines replaced by a 2 MW hybrid propulsion unit. A power of 1-2 MW also applies to the United Technologies DHC-8 demonstrator.

8.1.4 Electrification of airplane components

Many components/systems of conventional aircraft such as actuation, de-icing, and air-conditioning are related to mechanical, hydraulic, and pneumatic sources of power, which are extracted via different ways from the aircraft engines. About 5% of the engine's total output is consumed for such non-propulsive systems. But the hydraulic and pneumatic systems have often suffered from a lack of reliability and high maintenance costs. Therefore, more and more electrical systems have replaced the conventional systems. Boeing introduced in their Boeing 767 with electrical cabin equipment, avionics, landing gear actuation, etc. This concept is now popularly known as the More Electric Aircraft (MEA). “Fly by Wire” (FBW) systems, electrically actuated thrust reverser, hybrid electro-hydraulic actuation systems for wing and tail flight control surfaces, electrically powered environmental control (air-conditioning) system, electrically actuated brakes etc. were introduced later. The higher electrification leads to reduced weight, greater reliability, lower maintenance costs and increased efficiency and finally to lower emissions. Furthermore, smart electronic management makes MEA potentially more compatible with new digital technologies.

An overview of the today and next-generation MEA functions gives the following table:

Table 8.1: Selected MEA functions in today and next-generation aircraft

<table>
<tr><th></th><th>Airbus A320</th><th>Airbus A380</th><th>Boeing 787</th><th>Next Generation</th></tr>
<tr><td>Deicing</td><td rowspan="2">Pneumatic</td><td rowspan="2">Pneumatic</td><td rowspan="5">Electric</td><td rowspan="5">Electric</td></tr>
<tr><td>Environmental control system</td></tr>
<tr><td>Avionics</td><td rowspan="2">Electric</td><td rowspan="2">Electric</td></tr>
<tr><td>Cabin systems</td></tr>
<tr><td>Braking</td><td rowspan="3">Hydraulic</td><td rowspan="3">Partly electric</td></tr>
<tr><td>Flight controls</td><td rowspan="2">Hydraulic</td><td rowspan="2">Partly electric</td></tr>
<tr><td>Landing gear, thrust reversers</td></tr>
<tr><td>Total aircraft power</td><td>< 200 kW</td><td>600 kW</td><td>1 000 kW</td><td>> 1 000 kW</td></tr>
</table>

In most cases, the electrical energy is generated via the aircraft engine. During ground operations, however, the engine is not switched on and the power is supplied via cable or during taxiing by APUs (Auxiliary Power Unit). The APU has an efficiency of < 20 % and emits noise and CO_2, NO_x. A PEMFC driven APU does not have these disadvantages[xxxvii]. In airplanes the primary electrical system also incorporates batteries mainly used during pre-flight to power up the electrical systems. Some electrically powered fixed equipment such as the Emergency Locator Transmitter (ELT), Cockpit Voice Recorders (CVR) and Flight Data Recorders (FDR), will have their own dedicated batteries.

Electrochemical power sources (ECPS)

There are different energy sources for storing and supplying the necessary electricity, e.g.

- Batteries can retain a significant electrical charge, although their weight still limits the range achievable.
- Fuel cells are similar to batteries but draw their reactants from an external source.
- Ultracapacitors can store a limited amount of energy for short bursts of high-power use
- Power cables connect to a ground-based supply.
- Solar cells convert sunlight directly into electricity.
- Thermoelectric generators
- Microwave energy has been beamed from a ground-based source.

The main energy source for electrical airplanes is electrochemical power sources (ECPS) based on electrochemical energy conversion principles. They include rechargeable batteries, fuel cells, and supercapacitors.

Due to their high specific energy mainly batteries and fuel cells are used in aviation systems. Supercapacitors have lower specific energy but a very high specific power and are therefore sometimes utilized in hybrid systems with batteries and fuel cells to take care of the system peak power.

The fuel cell system consists of two parts, the power-generating fuel cell stack (A) and the energy determining hydrogen tank (B). The energy of the fuel cell system is therefore determined by the mass of hydrogen (B) which is relatively low in relation to the mass of batteries. This affects the mass ratio of batteries to fuel cells. $m_{batt} = m_{FC}$ is observed at a critical energy/operation time (E_{crit}, t_{crit}). At E, t < E_{crit}, t_{crit} the battery mass is lower than the FC mass and at E, t >E_{crit}, t_{crit} the FC mass is lower as the battery mass – see Figure8.17.

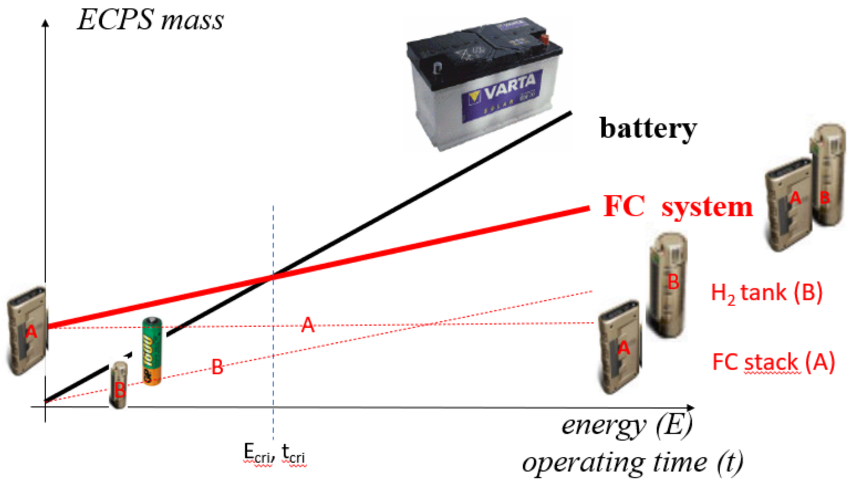


Figure 8.17: Mass of ECPSs (battery and fuel cell) vs. energy/operating time

That means for larger flight ranges FCs as ECPS are in principle to prefer.

The state of the art (Generation 2 – see **Figure**) of the specific energy of battery cells is about 250 Wh/kg, which is related(factor ca. 0.65) to about 160 Wh/kg.

Very great efforts are being made to increase the specific energy, especially pushed by the car manufacturers. There are 4 general ways to go for the increase of the specific energy: material optimization, electrode/cell optimization, new materials for Li-Ion batteries, and new battery systems. Especially the new systems (post-Li-ion systems) as Li-S (ca. 400 Wh/kg cell, Li-air (>> 500 Wh/kg cell) and Li solid-state systems (ca. 400 Wh/kg cell) are a hope move.

Caused by low power and a low lifetime of Li-S and Li-Air batteries for the time being the development is concentrated on solid-state battery which is based on the use of a metallic Li-anode.

In general with following developments of batteries related to the specific energy and time of market introduction can be expected -Figure 8.18.

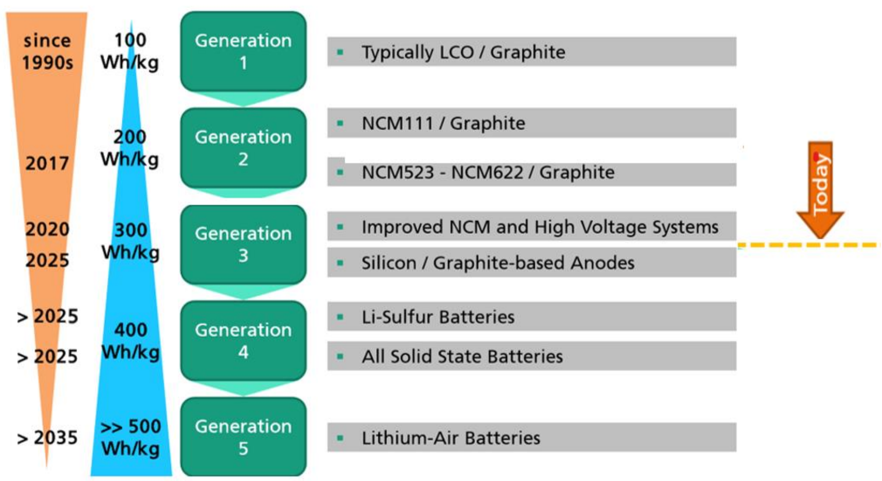


Figure 8.18: Roadmap of the cell development related to the specific energy and time of market introductionxxxviii

That means between 2025- 2030 cells are available with 400 Wh/kg or on the battery level of about 270 Wh/kg. From 2030…35 cells will have > 500 Wh/kg and batteries 333 Wh/kg.

This is a large improvement over the state-of-the-art, but not yet enough for the electrification of larger passenger airplanes with ranges of < 1000 km.

The state-of-the-art of specific power of PEMFC systems is about 1,5 kW/kg and 8 kW/kg are expected[xxxix]. The concrete specific energy depends on the hydrogen storage capacity. Usually, 500 – 1000 Wh/kg are reachable with H2 tanks, which fit the plane.

Besides the discussed important energy and power data of ECPS, the safety of ECPS are mandatory, especially in aviation. Problems with the transport of batteries were reduced by different regulations, which request a special test of the batteries (UN Model Regulation, Part III, subsection 38.3), discharge of the battery during air transport to 40 % SOC, which reduced the energy, mass limitations for the transport, or transport ban of Li batteries in passenger aircraft except for batteries for personal use[xl]. Nevertheless, there was a total crash in 2010 of a Boeing 747-44F cargo aircraft transporting Li batteries from Dubai to Cologne, Germany[xl].

For batteries which are used permanently in airplanes, for both for propulsion and for electrification of airplane components the risk is much higher. Although the safety risk probability for Li-Ion batteries is with 0.1 ppm very low, there are some battery-related accidents observed xli. An internal short circuit on batteries caused probably by dendrites in two Boeing 787 Dreamliner (ANA Flight 692 from Yamaguchi-Ube to Tokyo-Narita in the air; JAL Flight 008 after touched down at Boston) lead to smoke and fire, that could be extinguished without personal injury xli, xlii, xliii.
So the safety of the batteries is a very important topic.

Reliable cost values for batteries and fuel cells for aviation applications are not available. But as an approximation cost of electric cars is used.

In dependence of the annual production rate and the FC system power for different years the following costs are calculated by the US DoE for PEMFC systems

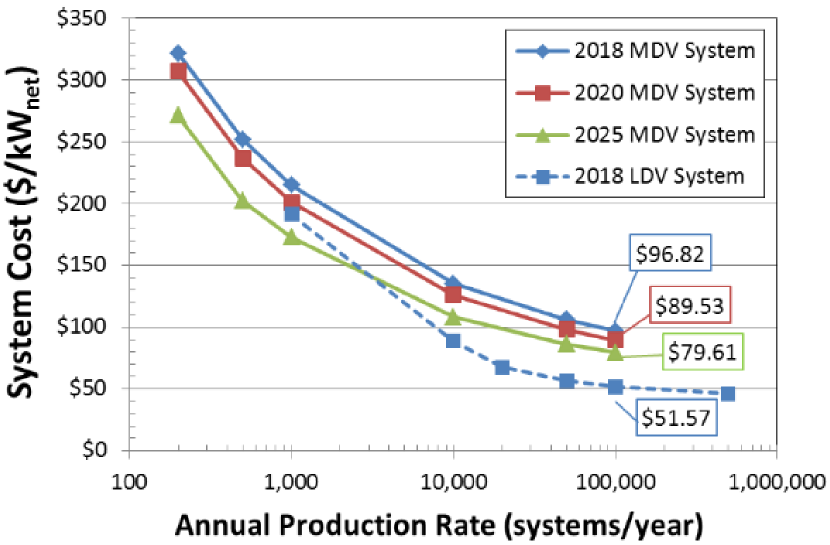


Figure 8.19: Cost estimation for PEMFC systems for light-duty vehicles (LDV) with 80 kW for medium-duty vehicles (MDV) with 160 kW vs. annual production rate and 2018, 2020, and 2025xliv

The costs for the hydrogen pressure tank type 4 (64,4 l H_2 @ 700 bar) are also dependent on the annual production rate. For 1,000 tanks/year are the costs at ~$1,250, for 100,000 tanks at ~$580 and for 500,000 tanks at $565 [xlv]. Liquid H2-tanks is not used for cars.

It is, however, to mention that the costs for FCs and the hydrogen tanks are only estimated. Furthermore, the given numbers refer to costs. The prices are about 1.4 times higher than the costs

The in Figure8.20 given prices for Li-Ion battery packs are up to 2018 real prices and for >2018 estimated.

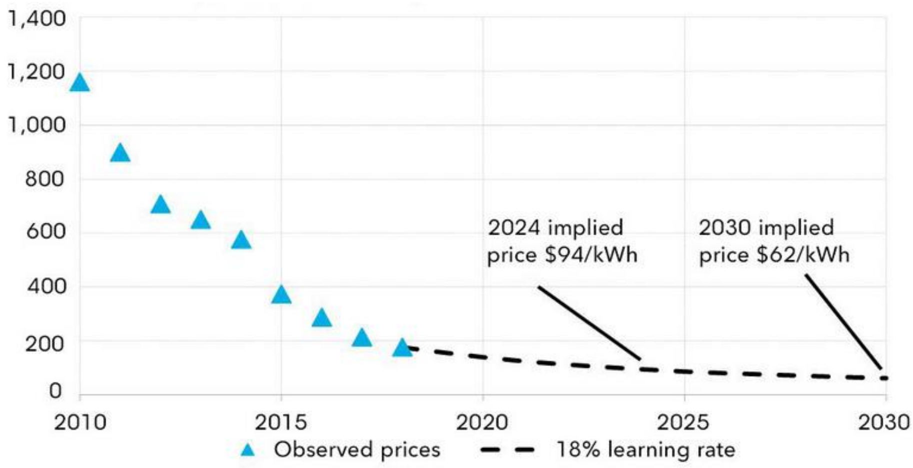


Figure 8.20: Li-Ion battery pack prices vs. yearsxlvi

Electric aircraft

As shown in equation 1 the range (R) is inversely proportional to the total mass of the aircraft:

$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{ECPS}}{m} \qquad (1)$$

with $m = m_{empty} + m_{payload} + m_{ECPS}$.

I.e. the range could be increased also by reduction of the empty weight of the plane (m_{empty}). Therefore, all aircraft components have to be weight-optimized.

While many parts are already weight-optimized via the longtime development of conventional combustion propelled aircrafts the electric motors have still room for improvement. For single-propeller, pure-electric aircraft are state-of-the-art the Siemens radial-flux permanent-magnet PM motors with 5 kW/kg. The YASA axial flux PM shows, however, 10 kW/kg and several designers promise 15-20 kW/kg for advanced electric motors.

Replacing metal body with plastics is another topic. This way is further developed to electrically smart plastics "massless energy" with dual functions: construction material and energy storage material. At the centre of interest are mechanical stable special carbon fibres with supercapacitors storage properties[xlvii]. Lamborghini and MIT are developing this system for cars.

Outlook

Caused by the permanent air traffic growth of about 5 % annually[xlviii] (doubling every 15 years) and the worldwide climate problems the air industry has to find solutions to reduce its harmful contribution to the environment.

The targets for 2050 given in the European program *Flightpath 2050* are compared with the respective numbers from the year 2000:

- A 75-percent reduction in aircraft CO2 emissions,
- A 90-percent drop in nitrous oxide emissions
- A 65-percent cut in noise levels

There are many approaches to meet these numbers. A very important one is the electrification of airplanes with electrochemical power sources (batteries, fuel cells). A good overview of the airplane electrification is given by the IDTechEx report, "Manned Electric Aircraft 2020-2030"[xlix].

For the time being the flying range of electrical aircraft is limited by the specific energy of batteries and fuel cells. For today batteries with a specific energy in the region of about 200 Wh/kg, and planes with an L/D relation of 10 and a $m_{batt}/m_{airplane}$ relation of 0.4 the flight range amounted to ≈ 250 km. By changing the aircraft design (increasing L/D relation - larger wingspans), increasing specific energy of ECPS, or lowering the total airplane mass the range can be increased. The changes must be justifiable in terms of general safety, flight behaviour and the cost of the aircraft.

This relatively low specific energy of the battery limits flights with passenger aircraft over long distances. Even if the specific battery energy is increased by a factor of 2…2.5, as foreseen at ≥ 2030, long-range flights will be not possible with medium size airplanes (≥ 100 passengers). Besides the range also the weight of electric motors (plus turbines in case of hybrids) is an important parameter, which is related to the weight of the airplane.

But for flights with shorter ranges and with smaller planes and/or low payload the batteries specific energy is already sufficient. Vertical take-off and landing (VTOL) taxis, general aviation & recreational aircrafts, and regional & business aircrafts, and drones fit the general limitations in weight and range. So, with a market introduction of these applications can be expected in this decade.

Larger ranges with > 100 passenger aircrafts have only a change as battery/turbine hybrid, i.e. with the help of a conventional turbine.

An overview of the timetable of the development of the aviation electrification shows the following Figure8.21.

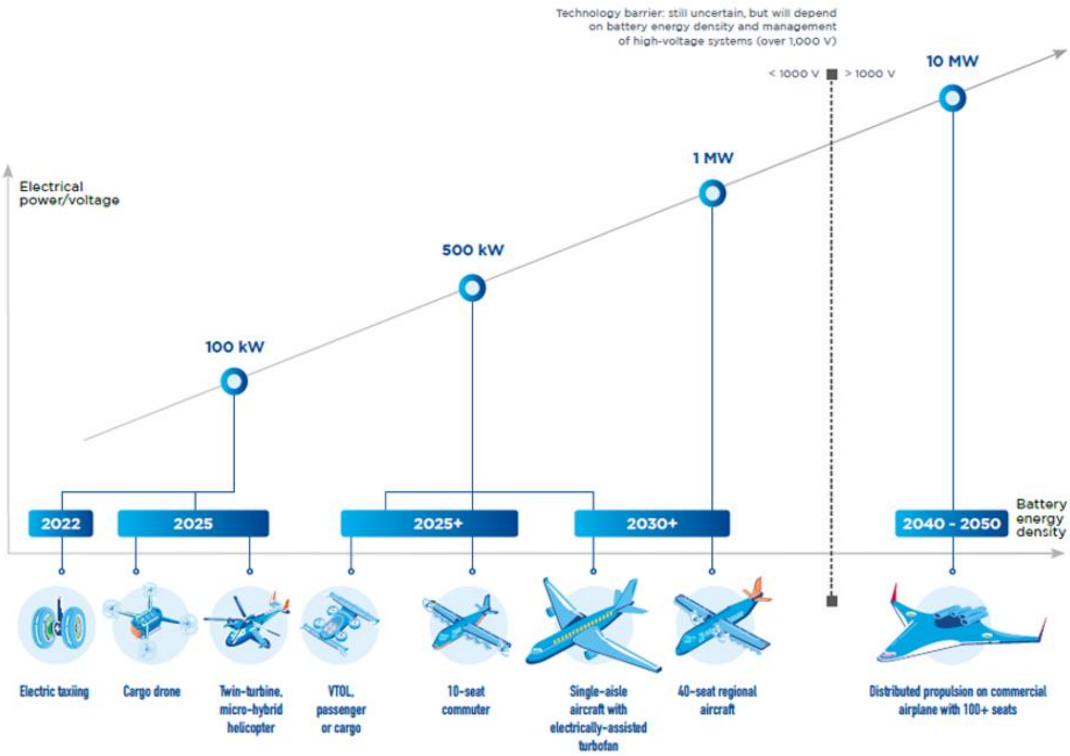


Figure 8.21: Timetable for the development of electric aircrafts /

In agreement with Figure8.21, the market introduction based on the power of the electric motor/ turbine is expected as follows[li]

Dependent on the power range and

- *Power Range 100 kW, market introduction by 2025*
  UAVs, helicopters with hybrid turbo shaft engine
- *Power Range 500 kW, market introduction by 2025+*
  VTOL aircraft, commuters with 10 passengers
- *Power Range 1 MW, market introduction by 2030+*
  Hybrid electric propulsion (turbofan electrically assisted) for short/medium range regional aircraft for 40 passengers.
- *Power Range 10 MW, market introduction beyond 2040…2050*
  Distributed propulsion on aircraft with 100 Pax

Although he electric airplane market is developing slowly, a study of 2020 estimated that Aircraft Electrification Industry will be worth $8.6 Billion by 2030 and key players will be Safran, Honeywell, Thales, United Technologies, GE Aviation, and Raytheon[lii].

Even though the development of aircraft is concentrated on the 100 kW – 500 kW class there are already today projects under the way to elaborate ways to develop eco-efficient commercial aircraft based on batteries and H2-FCs with at least 70 seats and a range of 2,000 kilometres to maturity by 2040 (see the project Exploration of Electric Aircraft Concepts and Technologies (EXACT)liii.

General, also hydrogen fuel cells are a propulsion solution especially for larger airplanes and larger ranges because the stored hydrogen volume determines their range and an increase of the stored hydrogen volume leads only to a relatively low increase of the mass. First developments of FC aircrafts exist but in general, the activities are on a low level. A commercial introduction of FC airplanes will be not before 2030.

A business case of electrical airplanes will be only developed if the costs and the environmental advantages are > 20 % of the conventional planes. Government restrictions as CO2 emission limits as for cars could be political support the development of electrical airplanes.

Besides technical questions as the energy of ECPSs and mass of the airplane also infrastructure questions (landing places, battery charge and H2 fueling points, etc.), air traffic control questions (air surveillance, possible routes, restricted areas etc.), and legislation questions as e.g. certifications are important. This is valid especially for vertically taking off air taxis (VTOL) because this is a new aircraft category which has little in common with conventional aircrafts.
For VTOLs now the European Aviation Safety Agency (EASA) has developed a framework for electric and hybrid-electric aircrafts, which are the first specifications important for the developer of these aircraftsliv. The new class "small category", includes VTLOs with up to nine passengers and starting weight of 3,175 kilograms. EASA is also responsible for certifications of electric airplanes in Europe. The first-ever certified (June 2020) full electric airplane by EASA after 3 years audits is The Pipistrel Velis Electro (Virus SW 128 – see 0).

8.2 Additive Manufacturing

Additive manufacturing has several attractive features: (i) since it consists of adding layers it does not waste material, unlike such processes like milling that carve a part out of a larger block; (ii) it allows the manufacture of large complex specimens that would otherwise have to be built-up of smaller parts with junctions. At present additive manufacturing also has limitations: (i) it is a slow process more suited to laboratory use or limited production of prototypes than to large scale high-rate serial industry; (ii) the surface smoothness is dependent on the number of layers that cannot be excessive, thereby requiring subsequent operations to ensure a better finish. If the limitations of additive manufacturing can be overcome there are promising prospects: (i) producing parts locally and as needed instead of transporting them from large stocks in a warehouse; (ii) coupled with digital imaging and sensing producing replicas and replacements for damaged parts already out-of-stock or unavailable. These features will become more useful as widens the range of materials suitable for additive manufacturing and their physical properties. Additive manufacturing is one of the contributors to more efficient production (section 8.3).

8.3 Efficient Production

Industrial sectors like automotive have taken the lead in efficient production relative to aeronautics due to a combination of factors including (i) much higher production rates (tens of thousands instead of tens) per month justify a larger investment in automation; (ii) less long-lead production items allow short start-to-finish production cycles (hours instead of months); (iii) smaller numbers of simpler parts with less stringent quality standards facilitate higher throughput. There are also counter-factors that favour aeronautics: (i) higher added value justifies bigger investments in quality and efficiency; (ii) large order backlogs if they are achieved give a measure of long-term stability. Some of the key concepts of efficient production read across production volume, value and rate and include: (i) just-in-time delivery avoiding large and costly static inventories; (ii) work planning that maximizes human motivation and efficiency; (iii) the right mix of automation and human intervention. The more complex world of aeronautics compared with other sectors provides opportunities for cross-fertilization in new technologies and their efficient utilization and management.

The next stage in the evolution towards efficient production is known as "4.0" and in a topic of major interest (Key Topic T8.1).

KEY TOPIC T8.1 EFFICIENT PRODUCTION 4.0

T8.1.1 Introduction

Based on the increase and advance of digitalization within the factories, the conjunction of internet and oriented technologies in the area of "smart" machines and sensors, another new and essential industrial revolution named Industry 4.0 has been born. The term *Industry 4.0* refers to the combination of several major innovations in digital technology, all coming to maturity right now, all poised to transform the energy and manufacturing sectors. These technologies include advanced robotics and artificial intelligence; sophisticated sensors; cloud computing; the Internet of Things; data capture and analytics; digital fabrication (including 3D printing); software-as-a-service and other new marketing models. Advanced digital technology is already used in manufacturing, but with Industry 4.0, it will transform production. It will lead to greater efficiencies and change traditional production relationships among suppliers, producers, and customers - as well as between human and machine. Nine technology trends form the building blocks of Industry 4.0. (Figure 8.22).

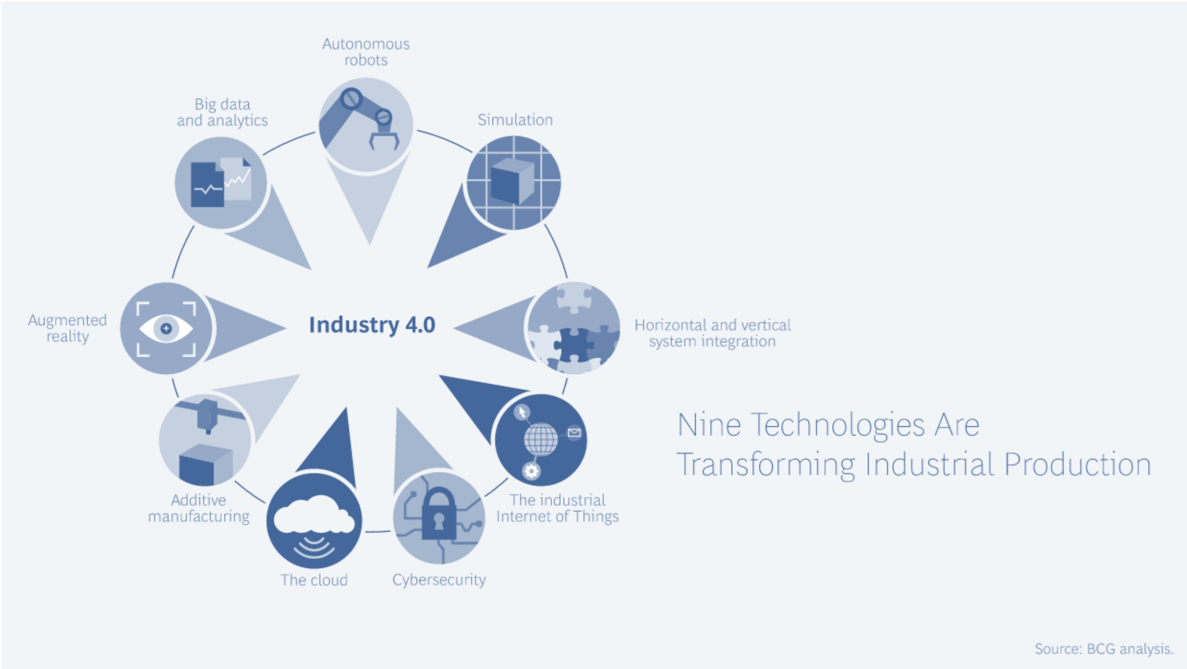


Figure 8.22 - Nine foundational technology advances powering transformation Industry 4.0

T8.1.2 Nine Technologies Transforming Industrial Production

T8.1.2.1 Big Data and Analytics

Analytics based on large data sets where it optimizes production quality, saves energy, and improves equipment service. In an Industry 4.0 context, the collection and comprehensive evaluation of data from many different sources - production equipment and systems as well as enterprise - and customer - management systems - will become standard to support real-time decision making.

Big data arose due to the emergence of three major trends. First, it has become economical to generate a broad kind of data, due to inexpensive storage, sensors, smart devices, social software, multiplayer games, and the Internet of Things. Second, it has become inexpensive to process huge amounts of data, due to progress in multicore CPUs, solid-state storage, cloud computing, and open-source software. Thirdly, not just database administrators and developers, but many more people (such as decision-makers, domain scientists, application users, journalists, and ordinary consumers) have become involved in the process of generating, processing, and consuming data.

Currently, the aviation industry adopts on Condition/Preventive maintenance procedures due to its operational efficiency and it depends upon the failure mode calculations made after testing a part under circumstances. These conditions may fluctuate depending on the external factors/human errors which may result in the variation in the lifetime of components, in turn, reducing the operational efficiency of the aircraft.

A study by FAA states that during a year jet engine generates data equivalent to 20TB. Basically, most of this data is not used for any of the analytics purposes since this data is unstructured. Big data analytics can be used to predict the fault in the component by analysing data obtained from various sensors and account of the specific component attached to an aircraft or fleet in which it is present.

Commercial airline manufacturers are extending their digital products in a range of ways. A typical aircraft has millions of parts. The amount of data output is immense and is increasing rapidly with a new generation of aircraft. Legacy aircraft used to capture 125+ flight parameters. The Airbus A320, for example, produces 20,000 data parameters but the latest A350 has 400,000 and data output of some 250GB per flight. Boeing 787 captures more than 1000 flight parameters with some reports claiming half a terabyte of data per flight. This explains the big data explosion in aviation. This data is being used to improve flight operations, safety and efficiency, enhance the passenger experience and deliver better predictive and customised maintenance.

Apart from flight data, a large amount of data gets generated in repair shops, inventory systems and by various regulatory organizations as well. Analysing such big data can help in improving flight safety, reducing operational delay, better inventory management of spares, predictive maintenance of various equipment on board, improving the fuel economy of the fleet etc. Honeywell Aerospace has been a pioneer in providing flight data solutions for predictive maintenance of parts through its tools and data sources like PTMD (Predictive Trend Monitoring and Diagnostics). Its focus is to leverage the latest tools and technologies in big data analytics space to improve these predictive maintenance offerings. Using big data and analytics infrastructure, Honeywell Aerospace has enabled analysis of large data from ACMS (Aircraft condition monitoring systems) and various repair databases and found outliers and hidden trends in the data.

T8.1.2.2 Autonomous Robots

Manufacturers in many industries have long used robots to tackle complex assignments, but robots are evolving for even greater utility. They are becoming more autonomous, flexible, and cooperative. Eventually, they will interact with one another and work safely side by side with humans and learn from them. These robots will cost less and have a greater range of capabilities than those used in manufacturing today.

Robots improve the productivity favouring the savings on production and eliminating problems of lack of qualified manpower. Robots improve the quality of work by taking over dangerous, tedious, and dirty jobs that are not possible or safe for humans to perform. The high performance, low investment cost and most of all the adaptability of robots makes them the perfect choice for an efficient and easy automation solution. In this way, special software developed for robotics helps to improve the repeatability and the accuracy of robots' positioning. This feature contributes to meet the requirements of manufacturing aviation. Due to being known as very conservative, the aerospace industry usually uses successful assembly methods that have already been proven to work in the past. But, in the past couple of years, the general attitude, in terms of assembly tasks, has started to change in the aerospace industry. Aircraft manufacturers tend to use robotics on some manufacturing applications to perform tasks that require precision and rigidity on big parts. Investments with robots on aircraft manufacturing can be beneficial when the payback is feasible.

For example, KUKA, a European manufacturer of robotic equipment, offers autonomous robots that interact with one another. These robots are interconnected so that they can work together and automatically adjust their actions to fit the next unfinished product in the line. High-end sensors and control units enable close collaboration with humans. Similarly, industrial-robot supplier ABB is launching a two-armed robot called YuMi that is specifically designed to assemble products (such as consumer electronics) alongside humans. Two padded arms and computer vision allow for safe interaction and parts recognition.

Boeing was an early adopter of robots for painting aircraft and has facilities around the globe that deploy drilling and fastening robots on its aircraft assembly lines.

Boeing worked closely with KUKA Systems to develop an advanced automated manufacturing process for its wide-body commercial airliners. Called Fuselage Automated Upright Build (FAUB), the robotic production line assembles the forward and aft fuselage sections of the Boeing 777 jetliner. Several aspects of this robotic assembly line make it unique.

Traditionally, the riveting process is done manually with mechanics positioned on both sides of the fuselage, performing repetitive movements that place considerable strain and impact stress on their shoulders, arms and hands. In a costly and time-consuming process, the massive fuselage must be rotated so mechanics can ergonomically access the riveting locations. In the FAUB workspace, the fuselage remains "upright" throughout the entire build. Because unlike humans, robots can work at any angle.

According to Boeing, the process also simplifies the build by using determinant assembly (part-to-part indexing) for panel and floor indexing. A determinant assembly provides for a quicker process by using features of the parts, such as drilled holes, to quickly align components without requiring additional tooling or fixtures.

Workers begin the build by loading and assembling the floor beams and frames, and then synchronous robots work on the fuselage panels, both longitudinal and circumferential splices. Working from both sides of the fuselage, KUKA robots work in pairs to concurrently drill and countersink holes, insert fasteners, and complete the riveting.

KUKA Systems also developed the multifunctional end effector for the robot, which clamps the different material layers that make up the fuselage, and then drills, fills and bucks – all with one end-of-arm tool.

The FAUB production line is in residence at Boeing's mammoth factory in Everett, Washington. The aircraft manufacturer is currently using the process at a low rate of initial production. When at full rate, several pairs of KUKA robots will work in tandem installing approximately 50,000 fasteners per fuselage.

According to Boeing, the first 777 assembled with the FAUB process was delivered in December 2015. The robotic assembly system will be drilling, filling, and bucking the fuselages of the new Boeing 777X aircraft when it eventually enters production (the B777X is currently in early flight testing with some pending engine and certification issues). With FAUB, fuselage sections will be built using automated, guided robots that will fasten the panels of the fuselage together, drilling and filling the more than approximately 60,000 fasteners that until today were installed by hand.

Boeing reports that the new automated process helps with areas that cause the greatest ergonomic issues, but expects that other residual benefits will follow, including quality, cost, and flow. Quantifiable performance metrics will be made public when production reaches full rate.

Composite materials have been integral to the aviation industry for some time now. Coveted for their structural strength and lighter weight compared to metallic materials, composites contribute to better fuel efficiency and reduced airplane emissions. AFP (automated fibre placement) processes use computer-guided robotics to lay up to one or several layers, called tows, of carbon-fibre tape onto a mould to create a composite aerostructure.

The aerostructures manufacturer currently uses custom automation, or large gantry systems with multi-axis heads, for AFP processes on composite parts for the Airbus A350 XWB and Boeing 787 jetliners. But the use of robots for AFP is an area of interest.

To fabricate the composite parts of the giant wings of Boeing's 777X, Mukilteo-based engineering firm Electroimpact has designed and built a new generation of robotic machines that have not been previously shown to outsiders. Those are 30-foot-tall, 3-D printers, each costing tens of millions of dollars.

Precisely placing layer upon layer of carbon-fibre strips infused with epoxy resin, one of these AFP machines builds up the 777X's composite wing skin, producing single piece 110 feet long and 20 feet across at the widest end near the fuselage.

Using these technologies of Making the skins and spars of such a giant wing in single full-length pieces is new. It should reduce the cost of manufacturing and save some weight because there are no joins.

Using a wholly different method, the composite wing spar of the 787 is made in three sections by Mitsubishi Heavy Industries in Japan. In the U.K., Airbus supplier GKN uses AFP machines to fabricate the spars of the A350 wing, also in three sections.

T8.1.2.3 Simulations

In the engineering phase, 3-D simulations of products, materials, and production processes are already used, but in the future, simulations will be used more extensively in plant operations as well. These simulations will leverage real-time data to mirror the physical world in a virtual model, which can include machines, products, and humans. This allows operators to test and optimize the machine settings for the next product in line in the virtual world before the physical changeover, thereby driving down machine setup times and increasing quality.

For example, Siemens and a German machine-tool vendor developed a virtual machine that can simulate the machining of parts using data from the physical machine. This lowers the setup time for the actual machining process by as much as 80 percent.

Increasingly, simulations have been used in industrial operations, from the engineering phase, products' modelling and definitions of materials and production processes. Simulations compare on real-time data the physical world with a virtual model, which includes machines, products, and people. This allows operators to test and optimize the machine settings for the next product on production in a virtual environment before changing to the physical condition, thus reducing the downtime of machine setup and increasing the quality of the products. It consists of a virtual integration on the production shop floor, including equipment, products, planning, data and efficiency of operation. Digital manufacturing is also used to detect fails and interruptions of the production to reduce downtime, based on a virtual machine that can simulate the whole process.

T8.1.2.4 Horizontal and Vertical System Integration

Most of today's IT systems are not fully integrated. Companies, suppliers, and customers are rarely closely linked. Nor are departments such as engineering, production, and service. Functions from the enterprise to the shop floor level are not fully integrated. Even engineering itself - from products to plants to automation - lacks complete integration. But with Industry 4.0, companies, departments, functions, and capabilities will become much more cohesive, as cross-company, universal data-integration networks evolve and enable truly automated value chains.

The setting for vertical integration is the factory. A factory owns several physical and informational subsystems, such as actuators and sensors, control and production management, manufacturing, and corporate. Vertical integration refers to the integration of the various IT systems at the different hierarchical levels in order to deliver an end-to-end solution. In the field of production and automation engineering and IT, horizontal integration refers to the integration of the various IT systems used in the different stages of the manufacturing and business planning processes that involve an exchange of materials, energy and information both within a company (e. g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks). These new value creation networks are real-time optimized networks that enable integrated transparency and offer a high level of flexibility.

For instance, Dassault Systèmes and BoostAerospace launched a collaboration platform for the European aerospace and defence industry. The platform, AirDesign, is a scalable collaboration platform available as a service on a high-security, private cloud or on-premise. It consists of a neutral workspace for advanced OEM (Original Equipment Manufacturer) and partner PLM (Product Lifecycle Management) collaboration, design and manufacturing. Considered the next-generation platform for collaboration and exchange, it has been designed to integrate all the key industry players, from OEM to small and medium business enterprises.

AirDesign drastically reduces operational costs for all partners through a single infrastructure, common exchange methods, open standards, and easy access, all without adversely impacting existing information systems. All the primary European OEMs jointly requested and defined this platform in order to facilitate exchanges, support their suppliers' ecosystems and generate new opportunities with services.

T8.1.2.5 The Industrial Internet of Things (IoT)

Today, only some of a manufacturer's sensors and machines are networked and make use of embedded computing. They are typically organized in a vertical automation pyramid in which sensors and field devices with limited intelligence and automation controllers feed into an overarching manufacturing-process control system. But with the Industrial Internet of Things, more devices - sometimes including even unfinished products - will be enriched with embedded computing and connected using standard technologies. This allows field devices to communicate and interact both with one another and with more centralized controllers, as necessary. It also decentralizes analytics and decision making, enabling real-time responses.

Bosch Rexroth, a drive-and-control-system vendor, outfitted a production facility for valves with a semi-automated, decentralized production process. Products are identified by radio frequency identification codes, and workstations "know" which manufacturing steps must be performed for each product and can adapt to perform the specific operation.

The IoT concept can be defined as the use of internet technologies. It covers the wireless connection, micro-electromechanical systems, software and Apps. This approach has helped the linkage between Operational Technology (OT) and Information Technology (IT) allowing unstructured machine-generated data to be analysed for monitoring that will orient improvements on production systems. Every "thing" will soon be networked. Even today, almost every electronic device is able to communicate with the Internet. Digitization is triggering rapid developments in any area and digitally networked processes in Industry 4.0 will make it possible to manufacture products at a low cost in a manner that is more flexible, energy-efficient, resource-saving and customized. Thus, aviation manufacturing has looked for a solution in order to integrate robots, systems and devices by tablets and smartphones via Apps.

GE credits itself for coining the term "Industrial Internet of Things" in 2012 and describes it as "the network of a multitude of devices connected by communications technologies that results in systems that can monitor, collect, exchange, analyse, and deliver valuable new insights like never before." GE is one of the companies that founded the Industrial Internet Consortium to accelerate the development, adoption, and widespread use of interconnected machines and devices, intelligent analytics, and people at work.

A fine example of General Electric's appetite for industrial innovation is the development of the core Integrated Vehicle Health Management application (IVHM) for GE Aviation. From medical imaging, to aircraft engines, energy and rail monitoring, GE and its affiliates monitor hundreds of thousands different devices, including ten thousand engines.

GE's IVHM application now provides 24/7 worldwide wireless connection to aircraft health status in the broadest sense – including prioritized alerts and analysis of airframe, systems, and engines. The latter can be bought, leased and financed by General Electric Aviation Services (GECAS) from various companies, including GE, CFM, Rolls-Royce, Pratt & Whitney, IAE and Engine Alliance. GECAS offers short-term leases ranging up to one year and operating leases up to a term of 20 years. The company provides the largest and most diverse pool of spare engines in the marketplace.

The many benefits of GE Aviation's IVHM application that keep increasing include: reduced unscheduled and scheduled maintenance; reduced return to service time; reduced overall operations and maintenance costs; automatic data downloads for Flight Operational Quality assurance (FOQA) and health; quick identification of fleet-wide issues; improved aircraft availability and technical support; ever new insights to aircraft operation and performance.

Through this comprehensive web-based aircraft health management service, GE made it possible for operators to monitor fleet trends and detect and predict anomalies earlier and with greater confidence.

An aircraft engine used to be just one of many parts and slowly became a commodity. To counter that trend, Rolls Royce packed its engines with sensors allowing for real-time data analytics to improve performance and safety. The company launched "Engine Condition Monitoring" that sends real-time engine performance metrics when the plane is mid-air to one of the company's R&D centres. The data can be analysed instantly, and any concerns will be communicated to an airline before the plane reaches its destination. The company operates hundreds of terabytes of data allowing it to compare engine performance across different flights, leading to more efficient solutions. For instance, Rolls Royce Trent 7000 engine allows Airbus's A330 to be 14% more fuel-efficient.

Rolls Royce also makes flights safer and more predictable. Traditionally, any irregularities in engine performance during a flight would trigger a full inspection upon landing, leading to delays. With data analytics, Rolls Royce can assess in real-time if a plane is safe for another journey or if it needs to undergo maintenance. It can also predict which maintenance actions need to be taken ahead of time to limit travel disruptions. Finally, comparing data across journeys allows capturing early-warning signs, decreasing potential risks.

Airbus is planning to use the concept of the Industrial Internet of Things (IIoT) to improve its internal manufacturing process. The French OEM wants its future manufacturing process to be driven by the intersection of people, data and intelligent machines.

T8.1.2.6 Cybersecurity

Many companies still rely on management and production systems that are unconnected or closed. With the increased connectivity and use of standard communications protocols that come with Industry 4.0, the need to protect critical industrial systems and manufacturing lines from cybersecurity threats increases dramatically. As a result, secure, reliable communications, as well as sophisticated identity and access management of machines and users, are essential.

Such a promising development is not without a degree of risk. Transitioning from silo-based operations to the open model of Industry 4.0, with its interconnected industrial systems and the Industrial Internet of Things (IIoT), means opening the door to systems with an intrinsically low level of security. The associated risks may be considerable, ranging from commercial data confidentiality (manufacturing secrets, intellectual property theft, etc.) to the protection of people and property in relation to critical activities.

To allow industry to benefit from the most innovative technologies, Thales offers a complete range of solutions and services to support the secure end-to-end digital transformation of production systems. Thales solutions encompass data acquisition directly on the shop floor (via secure IIoT solutions), data processing and display at the human-machine interface level, secure cloud storage and Big Data analytics for predictive maintenance and other applications. With this full range of capabilities, Thales is helping to improve industrial processes by integrating leading-edge technologies that are "Secure by Design".

T8.1.2.7 The Cloud

Companies are already using cloud-based software for some enterprise and analytics applications, but with Industry 4.0, more production-related undertakings will require increased data sharing across sites and company boundaries. At the same time, the performance of cloud technologies will improve, achieving reaction times of just several milliseconds. As a result, machine data and functionality will increasingly be deployed to the cloud, enabling more data-driven services for production systems. Even systems that monitor and control processes may become cloud-based.

Vendors of manufacturing-execution systems are among the companies that have started to offer cloud-based solutions.

T8.1.2.8 Additive Manufacturing

Companies have just begun to adopt additive manufacturing, such as 3-D printing, which they use mostly to prototype and produce individual components. With Industry 4.0, these additive-manufacturing methods will be widely used to produce small batches of customized products that offer construction advantages, such as complex, lightweight designs. High-performance, decentralized additive manufacturing systems will reduce transport distances and stock on hand.

For instance, aerospace companies are already using additive manufacturing to apply new designs that reduce aircraft weight, lowering their expenses for raw materials such as titanium.

For example, at the Airbus's Innovation Cell, the parts produced on Stratasys machines weigh 30–55% less than traditionally manufactured parts, reduce raw material used by 90%, and cut total energy used in production by up to 90% compared to traditional methods. The production has reduced the total weight on each aircraft by up to one ton. By 2018, Airbus expects to print about 30 tons of metal parts every month. Similarly produced components are also included within in-service jetliners in the A300/A310 family.

Although additive manufacturing is very promising, with many achievements at the laboratory and prototype stage, large scale manufacturing still faces challenges. The choice of materials is limited to those available in powder form, with an increasing number of alternatives. Careful computer design of the production process is needed to achieve the possible weight savings, whereas poor planning can lead to overweight parts. The number of layers, and hence production times, determine surface roughness; to produce smooth parts in a reasonable time, the surface finish may need improvement as a consequence. Additive manufacturing is very sensitive to positioning, with small deviations leading non-identical parts. This is a major issue for certification that enforces stringent standards on repeatability.

A niche where additive manufacturing is enjoying some success is in parts for spacecraft. Since putting 1Kg in orbit costs 10K euros, satellite designers are willing to pay 2 to 4K per Kilo of weight reduction for spacecraft parts. This allows for the use of expensive laser machines, careful computer design of the production process, use of high-quality powders and many layers for smooth though time-consuming finish. For parts produced in small numbers for spacecraft, there are no certification issues and long as they meet strict quality standards.

T8.1.2.9 Augmented Reality

Augmented-reality-based systems support a variety of services, such as selecting parts in a warehouse and sending repair instructions over mobile devices. These systems are currently in their infancy, but in the future, companies will make much broader use of augmented reality to provide workers with real-time information to improve decision making and work procedures.

For example, workers may receive repair instructions on how to replace a particular part as they are looking at the actual system needing repair. This information may be displayed directly in workers' field of sight using devices such as augmented-reality glasses.

Another application is virtual training. Siemens has developed a virtual plant-operator training module for its Comos software that uses a realistic, data-based 3-D environment with augmented-reality glasses to train plant personnel to handle emergencies. In this virtual world, operators can learn to interact with machines by clicking on a cyber-representation. They also can change parameters and retrieve operational data and maintenance instructions.

Augmented Reality (AR) is defined as an integration of digital information with the user's environment in real-time. It uses the real world and overlays virtual information on top of it to perform the augmentation. Digital data can be input to visual or sound condition. When applied to visual, 3D digital objects are loaded and rendered within the physical world often using a display device like a tablet or smartphone. Numerous advancements in AR have enhanced the feasibility of using AR in many applications. The advantages and benefits of AR have been widely applied by important aircraft manufacturers in the global market.

An important industrial application of AR is already used by Airbus. The solution of digital tools has been developed to assist the aircraft production process. This AR solution was named MiRA (Mixed Reality Application) by Airbus. MiRA is designed to reduce the inspection time of tens of thousands of brackets that hold hydraulic pipes and wire bundles in place in the plane, and late discoveries of damaged, wrongly positioned, or missing brackets. This application increases the productivity in production lines by using AR to scan parts and detect errors on structures. For example, on A380 aircraft, MiRA contributes to a time reduction of 80 % for inspection of brackets in the fuselage. Saving could be got due to the integration of AR with a tablet and a special pack containing sensor and software. Also, other gains related to discoveries of damages, wrongly positioned or missing brackets have been reduced by 40 %. A specific application of AR technology has been used on Airbus factories. On the shop floor, tablets and sensors are installed inside the aircraft fuselage in order to track the position of parts and relate them to full-scale CAD models of the real. So, this allows downloading an image of the part in the area where they are working to ensure that they have fixed it correctly. Location tags attached inside the fuselage interact with the sensors to allow the visualization of the tasks from any work location. Another saving is the reduction of the time to inspect brackets inside an A380 fuselage, which hold systems such as hydraulics pipes.

MiRA technology has been developed by Airbus Group Innovation. Mira is now in use on the A320, A380, A350 XWB, A400M production lines in French, German, and Spanish Airbus plants. Inspection time for the 60,000 to 80,000 brackets in the A380 fuselage has dropped from three weeks to just three days.

Digital MockUp (DMU) is another concept that allows the description of a product, usually in 3D, for its entire life cycle. DMU is enriched by all the activities that contribute to describing the product. At Airbus, GPure system is used to prepare the Catia DMU of plane sections to inspect. This GPure automation process selects and optimises the necessary parts with their context for a given inspection scenario and adapts them by adding SAP metadata used by MiRA to assist the operator using its tablet PC in the plane under assembly.

8.4 Telecommunications

Telecommunications is a major innovation and growth sector in modern societies that become readily embedded in aeronautics technologies and the services they provide, including navigation and air traffic management, on-board monitoring and preventive maintenance, flight safety and security, etc. The expanding flow of information risks saturating the frequency spectrum and forces the trend to higher frequencies to achieve larger bandwidths and data rates. The larger flow of information can also create vulnerabilities if the content is corrupted or interrupted by unintentional failures or interferences or calculated or malicious actions.

The progress in telecommunications supports not only flight operations but also earlier stages of aircraft design and production. Nevertheless, one of the main applications of telecommunications in aeronautics remains air traffic management (Key Topic T8.2).

KEY TOPIC T8.2 TELECOMMUNICATION IN ATM

T8.2.1 Current Status

Since the first steps in aeronautics in the 20th century, telecommunications have played a key role within this field; this is due to the fact that air traffic is based on the use of telecommunications in such a way that most of its applications within this field were introduced decades ago. Nowadays telecommunications still play a key role within the current air traffic network and it is expected to continue occupying its position as its core.

Telecommunications allow the provision of air navigation services, both those services addressed to provide to aircraft's positioning and guidance capacity and those services that allow to carry out their movement in the presence of other aircraft in a safe, efficient and effective way. Thus, the cluster of air traffic management (ATM), communication, navigation and surveillance (CNS), meteorological (MET) and aeronautical information (AIS) services are called air navigation services. Likewise, ATM services are divided into three different services: air traffic flow management (ATFM), airspace management (ASM) and air traffic services (ATS) which are composed in turn by air traffic control (ATC), flight information services (AIS) and alert services (AL). Telecommunications are the core of this network in such a way that they allow, as an example, communications air to air, air to ground, ground to ground, as well as aircraft navigation or surveillance through the application of radio frequencies. Thereby, available communication and surveillance systems are essential for the correct functioning and effectiveness of air traffic control services as well as equipment based on radio waves is essential for the correct aircraft navigation.

As the numbers of equipment's and applications that use radiofrequency is large, the radio spectrum is close to being saturated. Thus, there are specific areas of the spectrum whose frequencies are reserved for aeronautical radio-communication and radio-navigation services. These areas are classified by bands, according to International Telecommunication Union (ITU) and Institute of Electrical and Electronics Engineers (IEEE) criteria. The following colours have been used to classify the radiofrequency usages within aviation network:

- Red: ATM Infrastructure – Communication
- Green: ATM Infrastructure – Surveillance
- Blue: ATM Infrastructure – Navigation
- Purple: Avionics and Airborne equipment

Bands	Frequency spectrum	Aviation usages	Types of services
LF & MF	130 – 535 kHz	Non-Directional Beacon (NDB)	Aeronautical Radionavigation Service
HF	2850 – 22000 kHz	Air-ground communication (HF voice and data)	Aeronautical Mobile (Route) Service
	3023 & 5680 kHz	Search and Rescue	Aeronautical Mobile (Route) Service
VHF	74.8 – 75.2 MHz	Marker Beacon	Aeronautical Radionavigation Service
	108 – 117.975 MHz	VOR/ILS localizer GBAS/VDL Mode 4 (voice and data)	Aeronautical Radionavigation Service Aeronautical Mobile (Route) Service
	117.975 – 137 MHz	Air-ground and air-air communications (VHF voice and data)	Aeronautical Mobile (Route) Service
	121.5, 123.1 & 243 MHz	Emergency distress frequency	Aeronautical Mobile (Route) Service
UHF	328.6 – 335.4 MHz	ILS glide path	Aeronautical Radionavigation Service
	406 – 406.1 MHz	Emergency locator transmitter (ELT)	Mobile-Satellite Service
UHF or L	960 – 1164 MHz	Distance Measuring Equipment (DME) TACAN LDACS (for datalink) LDACS (for Alternative-PNT)	Aeronautical Radionavigation Service Aeronautical Mobile (Route) Service
	978 MHz	Universal Access Transceiver (UAT)	Aeronautical Mobile (Route) Service
	1020 – 1040 MHz	Secondary Surveillance Radar (SSR)	Aeronautical Radionavigation Service

Bands	Frequency spectrum	Aviation usages	Types of services
	1080 – 1100 MHz	1090 Extended Squitter ADS-B Airborne collision avoidance system (ACAS)	
	1164 – 1215 MHz	DME/Global Navigation Satellite System (GNSS)	Aeronautical Radionavigation Service/Radionavigation-Satellite Service
	1215 – 1400 MHz	Primary Surveillance Radar (PSR)	Aeronautical Radionavigation Service
	1525 – 1559 MHz	Satellite Communications (FANS/ATN Baseline 1 and 2)	Mobile-Satellite Service (space-Earth)
	1559 – 1610 MHz	Global Navigation Satellite System (GNSS)	Aeronautical Radionavigation Service/Radionavigation-Satellite Service
	1610 – 1626.5 MHz	Satellite Communications (IRIDIUM)	Aeronautical Mobile-Satellite (Route) Service (space-Earth, Earth-space)
	1626.5 – 1660.5 MHz	Satellite Communications (FANS/ATN Baseline 1 and 2)	Mobile-Satellite Service (Earth-space)
UHF or S	2700 – 3300 MHz	Primary Surveillance Radar (PSR) Meteorological RADAR	Aeronautical Radionavigation Service Radionavigation Service/Radio Location Service
	3400 – 4200 MHz	Satellite Feeder Links to ATS Services in Africa	
SHF or C	4200 – 4400 MHz	Radio Altimeter Wireless Avionics Intra-Communications (WAIC)	Aeronautical Radionavigation Service
	5000 - 5250 MHz	Microwave Landing System (MLS) UAS CNPC*/Airport Surface Communication (AeroMACS)	Aeronautical Radionavigation Service Aeronautical Mobile (Route) Service/Aeronautical Mobile-Satellite (Route) Service
	5350 - 5470 MHz	Airborne weather radar	Aeronautical Radionavigation Service
SHF or X	8750 - 8850 MHz	Airborne Doppler radar	Aeronautical Radionavigation Service/Radio Location Service
	9000 - 9500 MHz	Precision Approach Radar (PAR)/Airborne weather radar/ASDE	Aeronautical Radionavigation Service/Radionavigation Service
SHF or Ku	13.25 - 13.4 GHz	Airborne Doppler radar	Aeronautical Radionavigation Service
	15.4 - 15.7 GHz	PAR/Airborne weather radar/ASDE	Aeronautical Radionavigation Service/Radio Location Service
SHF or K	24.25 - 24.65 GHz	ASDE	Radionavigation Service
SHF or Ka	31.8-33.4 GHz	ASDE/Airborne radar	Radionavigation Service

Table 8.2 - Aviation radiofrequency usages
Source: Aviation Usages of Frequency Spectrum [1]

* UAS CNPC: Unmanned Aircraft System Command and Non-Payload Communications

T8.2.2 Future Outlook

What can be noticed from Table 8.2 is that radio frequencies related to aviation network fill a wide area within radio spectrum that results in its almost saturation. However, this is not a recent issue due to that most of radio-based equipment was introduced along the 20th century; thereby radio spectrum dedicated to aviation started to be saturated long time ago. For example, the very first radio equipment began to be used in the late 1920s when weather updates and request help with navigation were transmitted through radio by two-way communications. At the same time, began the use of radio for navigation through radio marker beacons and 4-course radio range systems. During the next decade, the 1930s, the VHF omnidirectional radio range (VOR) started to operate helping pilots to navigate by instrument and it has become a primary NAVAID for decades owing to it has been globally used to define routes and support approach procedures. Likewise, the instrument landing system (ILS) was selected by ICAO as primary landing aid in 1946 and, after seventy years of successful operations and many improvements, it is still the most common precision approach and landing system used at airports.

As a consequence of the growth of air traffic and, likewise, of the growth of the number of NAVAIDs, the need for a higher number of radio channels was identified due to the congestion of radio spectrum. Thus, the saturation in the VHF frequency spectrum required for ground-air communication services forced stakeholders to reduce the separation between channels from 25 kHz to 8,33 kHz. This change in the frequency assignment has managed to increase the number of available channels in VHF band of aeronautical communications, which has allowed the creation of new control sectors and has contributed to increasing the air traffic management capacity. It all started in 1999, when some 30 states within the ICAO EUR region enforced mandatory carriage of 8,33 kHz radios above FL245 and, after that, the European Commission (EC) undertook to regulate the implementation of VHF 8.33 kHz in European airspace below FL245 down to FL195. The last effort in this field was carried out by the Single Sky Committee in 2012 when a new regulation extending the requirements for the 8.33 kHz spacing of the air-ground voice channel below FL195 was approved.

In this manner, the future scenario of communications relies on the use of the Aeronautical Mobile Satellite Service (AMSS) through the use of communications satellites SATCOM as well as the use of data link via VHF and HF. The data link is a method for connecting one location to another in telecommunications, in order to transmit and receive digital information. However, in aeronautics data link is a generic term encompassing different types of data links systems and subnetworks as is shown in the following Figure 8.23.

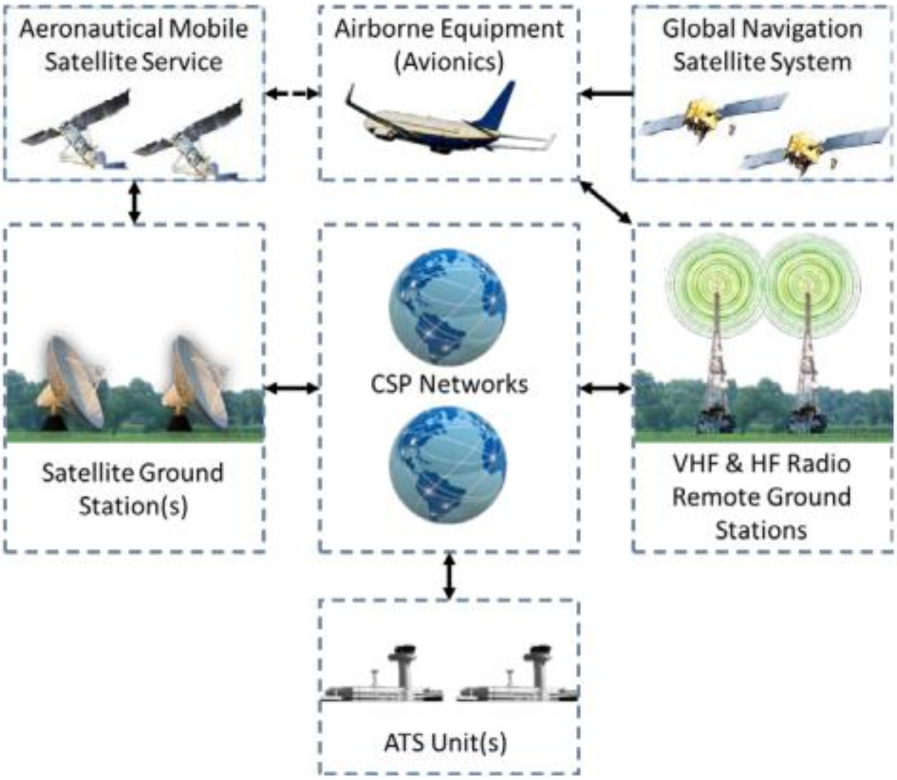


Figure 8.23 - Data Link System Overview

Source: FAA [5]

The data link is being widely spread within aviation framework due to it facilitates specific Air Traffic Management (ATM) operational functionalities such as Context Management (CM), Controller Pilot Data Link Communications (CPDLC), Data Link Flight Information Service (DFIS), Automatic Dependent Surveillance – Addressed (ADS-C) or Automatic Dependent Surveillance-Broadcast (ADS-B). For example, CPDLC is a means of communication between controller and pilot, using data link for Air Traffic Control (ATC) communications in which messages from an aircraft to the Air Traffic Service Unit (ATSU) may follow a standard format or maybe free text unlike messages from a controller which usually follow a standard format and require a response from the pilot.

One of the goals is that all of this comes together on the ground through a much more efficient, modern and global Aeronautical Telecommunication Network (ATN). ATN is an internetwork that permits ground, air-ground and avionics data subnetworks to exchange digital data for the safety of air navigation and the regular, efficient and economic operation of ATS. Nowadays, the system has constraints as it is terrestrial-based and not available over oceanic and remote continental areas and, besides, ATN is in limited use in Europe and it is not available in the US domestic airspace. However, communications via data link are already being used in certain airports and airspaces, allowing the obtaining of:

- Pre-departure clearances (PDC);
- ATIS information (D-ATIS);
- VOLMET information (D-VOLMET);
- Oceanic clearances (OCL).

It is expected that VHF communications still are an important communication way between aircraft and air traffic controllers in terminal areas, whilst it is expected that direct links replace HF communications between aircraft-satellite-ACCs (Airspace Control Centres). Thus, radio communications are expected to be maintained in service mainly for critical messages such as vectors to avoid traffic or landing clearances at congested airports as well as it is expected that it is a support for the data link. Likewise, digital communications allow a link ground-air more direct and effective which results in a benefit in the data exchange between operators, aircraft and ATS centres, in relief in the voice channels congestion and in a substantial decrease in odds of making a mistake. All of this results in better air traffic management.

On the other hand, traditional navigation has been based on the use of navaids located on the ground (Very High-Frequency Omnidirectional Range -VOR, Non-Directional Beacon - NDB, Instrument Landing System - ILS, Distance Measuring Equipment - DME) and autonomous (Inertial Navigation System INS). Navaids provided the backbone of the global air navigation system since they were introduced during the 20th century, and its development has been linked to the development of electronics. At present, navaids infrastructure is under a transition phase since the introduction and development of Global Navigation Satellite System (GNSS) that results in the change of navaids scene. Due to this, many of the navaids currently working are expected to be replaced by satellite-based systems.

The future of air navigation is determined by Performance-Based Navigation (PBN) future deployment which will allow limiting the use of navaids on the ground only for certain airspaces. According to PBN Navigation Strategy 2016 by FAA, PBN comprises Area Navigation (RNAV) and Required Navigation Performance (RNP) and describes an aircraft's ability to navigate in terms of performance standards. On the one hand, RNAV enables aircraft to fly on any desired flight path within the coverage of ground- or space-based navigation aids, within the capability of the aircraft equipment or a combination of capabilities. On the other hand, RNP is RNAV with the addition of onboard performance monitoring and alerting capability. A defining characteristic of RNP operations is the ability of the aircraft navigation system to monitor the navigation performance it achieves and informs the pilot if the requirement is not met during an operation. Common PBN specifications include RNAV 1, RNAV 2, RNP 0.3, RNP 1, as well as RNAV (GPS) and RNAV (RNP) approaches. In this manner, RNAV navigation allows flying any route specified by the user with the least possible constraints since there is no need to fly over the navaids on the ground. This is due to RNAV is based on the use of Global Navigation Satellite System (GNSS) with the support of Augmentation Systems (AS) based on satellites (Satellite-Based Augmentation Systems - ASBAS), on the ground (Ground-Based Augmentation Systems- GBAS) and onboard (Aircraft-Based Augmentation Systems - ABAS), which allow fulfilling the minimum requirements to operate as a unique navigation system. Concerning the future, it is expected that by 2030 PBN procedures and flexible routing are the standard method of navigation during normal operating conditions. Related to that, the number of VORs and ILSs will be gradually reduced as a result of rationalization. Additionally, due to increased and evolving training on PBN procedures and the evolution of decision support tools for the ATC and pilot community, automation tools and operations will be tightly integrated.

Thus, satellite-based navigation is likely to become an essential element due to it will transform air traffic management because it will allow attaining the full implement of RNAV navigation. Besides, its precise time reference is expected to be used in surveillance and communications strategic applications. Therefore, within GNSS network, the development and deployment of GALILEO system will be essential for the European Union owing to GALILEO has been designed to fulfil all the required features for aviation users hence it can be widely used, unlike GPS which is hardly certifiable unless augmentation systems like EGNOS are used. In this manner, GALILEO will be more accurate and reliable than GPS and it will also inform users about possible system failures (integrity).

8.5 Cybersecurity

The increasing reliance on computer systems tied by telecommunications links multiplies the entry points for disruptive and malicious intrusions. Aeronautics needs no less and perhaps more than many other sectors to implement security measures such as (i) isolation of safety-critical systems as far as it is possible to avoid external links; (ii) access protocols able to foil would be intruders through multiple layers that need not be complex; (iii) independent full-time monitoring of the network to locate local anomalies and prevent their spread; (iv) permanent updating of the list of risks to avoid being surprised by a new form of hacking; (v) general intelligence of security risks, actors and critical time periods; (vi) ability to isolate, re-configure and re-quality compromised systems in the shortest possible time scale; (vii) sufficient redundancy and alternative paths to restore lost capabilities. It is known that: (i) the only unbreakable code is that used only once; (ii) there is no 100% safe protection of software by software. Cybersecurity is and is likely to remain a game of constantly staying on top of new threats.

Cybersecurity is a major concern for air traffic management (Key Topic T8.3) but also in other sectors of aeronautical activity, including airline activities (Key Topic T8.4).

Cyber-vulnerabilities have been exposed at industry and government level, even in the largest aerospace programmes, like the F-35 Lightning II – Joint Strike Fighter Programme:

- Industrial espionage has used small sub-contractors with modest security resources to access up the supply chain to main contractors.
- Intergovernmental meetings among the representatives of participating nations have had uninvited, invisible "guests" from other nations.

These kinds of security breaches can compromise major systems, forcing large scale and costly redesigns.

KEY TOPIC T8.3 CYBERSECURITY IN ATM

T8.3.1 Current Status

Cybersecurity is a relatively new component of aviation security. Putting in context, aviation security consists of safeguarding civil aviation against acts of unlawful interference and this objective is achieved by a combination of measures and human and material resources. However, from a historical point of view, aviation security refers to unlawful physical acts like hijack of aircraft, destruction of an aircraft in service, hostage-taking on board an aircraft or at airports, introduction on board an aircraft or at an airport of a weapon or hazardous device intended for criminal purposes, use of an aircraft in service to cause death, serious bodily injury or serious damage to property or the environment, and so on. Unlike the previous unlawful acts, cybersecurity is about the prevention of and/or reaction to deliberate malicious acts undertaken via cyberspace to either compromise the system directly or wherever systems play a key role. While there is no standard definition of cyberspace it refers to the domain of information flow and communication between computer systems and networks and includes physical as well as purely virtual elements. Airport and ATM cybersecurity are aimed at limiting the effects of such cyber-threats and the impact on airport organization and operations and the overall ATM network.

Cybersecurity has become a real issue for aviation, driven by different factors such as the increasing interconnectivity of ATM which means that the impact of an attack may extend across a growing number of interconnected systems; the increased reliance on integrated data which means a high potential for operational disruptions if connectivity is lost; the migration toward common and Commercial Off The Shelf (COTS) components, underpinned by industry-standard protocols such as Internet Protocol (IP), with published vulnerabilities which mean that more people will have the technical background to launch attacks and more people will have access to core infrastructures through extended supply chains; and new methods of attack stemming from either criminal activities and/or state-sponsored actors, of increasing levels of sophistication. In summary, aviation cyberattack surface is growing due to more interconnected systems [2].

In order to ensure the identification of appropriate preventive security measures, the level of threat should be continually reviewed, and risk assessments carried out, taking into account international, national and regional situations and environments. In this manner, whenever a specific threat exists, selected and predetermined preventive security measures should be applied, commensurate with the associated risk assessment and the nature and severity of the threat. Therefore, as a cyber issue has been identified as an important risk for aviation security, it should be treated with the same importance as any other threat that affects aviation security [3].

As well as in air transport, cyberattacks are multiplying in many sectors causing serious issues. These include industries like banking, retail, health insurance or online businesses. Recent data refer that on a global scale, the average data breach exposes 25,575 sensitive consumer records and carries a total cost of $3.92 million, according to IBM's 2019 "Cost of a Data Breach" report.

Aviation can learn from other sectors about this issue, trying to develop a strong network where cyberattacks odds are reduced to a minimum and where cyber-related disruptions in operations are avoided. If these disruptions are not avoided, successful cyberattacks can cost up to tens of million dollars through immediate direct cost due to service interruption for hours or days and indirect cost for investigation and "clean" rebuilding of the system.

One of the keys to fighting successfully against cyberattacks is to identify the potential cyber-attackers. The main potential aviation threat actors are shown in the following Figure 8.24:

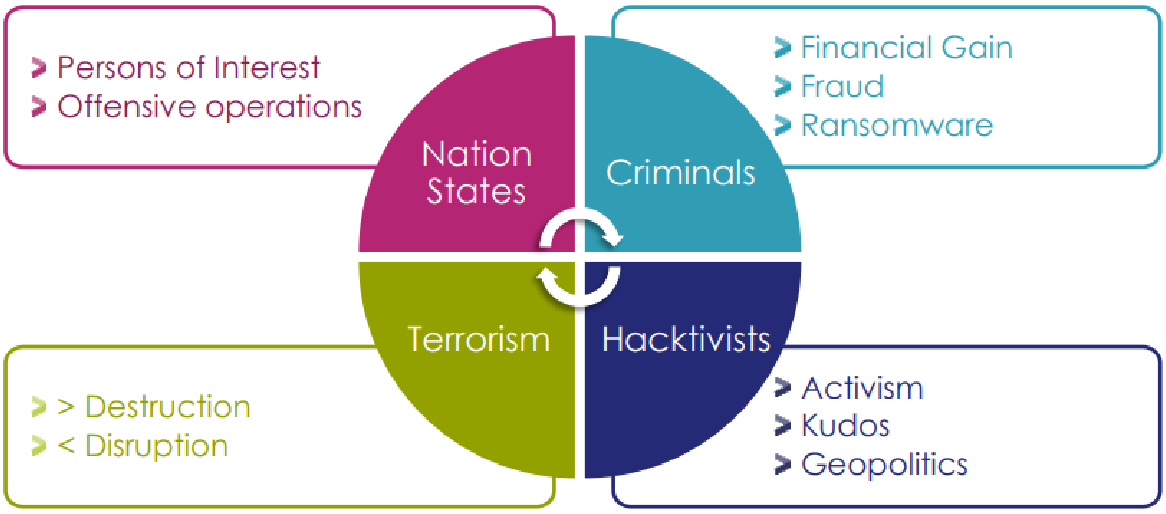


Figure 8.24 - Potential aviation threats actors

Source: THALES [4]

The potential cyber attackers that are shown in the previous Figure 8.24 can be explained as follows [2]:

- Insiders like employees, contractors, etc., who have legitimate access to sensitive information, either by accidental or deliberate misuse (e.g. when threatened by terrorists).
- Hacktivists, who have a cause to fight for such as political or ideological motives.
- Hackers or virus writers, who find interfering with computer systems an enjoyable challenge.
- Business competitors and foreign intelligence services are interested in gaining economic advantage for their companies or countries.
- Cyber-criminals, who are interested in making money through fraud or from the sale of valuable information.
- Terrorists, who are interested in obtaining and using sensitive information to launch a conventional attack.
- Organized crime, who are interested in obtaining financial reward or ransom in exchange for not provoking cancellations or flight disruptions.
- State cyber-forces, who have a large amount of resources at their disposal, state backing and are very highly skilled.

T8.2.2 Future Outlook

As today's cyber threat actors such as hackers, cybercriminals, hacktivists and terrorists are focused on malicious intent, the theft of information, profit and disruption, the safety and security of the global aviation system could become vulnerable to attacks on its information and data systems.

As one of the most complex and integrated systems of information and communications technology (ICT) in the world, the global aviation system is a potential target for a large-scale cyberattack, or for an attack on one or some of its elements in which possible impacts of a cyberattack range from endangering the safety of an aircraft to affecting operational reliability, financial health and business continuity. With the continual and rapid integration of new technologies, the aviation industry is becoming increasingly inter-connected and reliant on systems and, as technologies rapidly evolve, however, so too do the threats [6].

Although it is difficult that an airplane is hijacked or taken over by cybersecurity-related means any time soon due to regulators and manufacturers take care of that even before a new aircraft is designed, the airline's brand and business continuity are threatened by cybersecurity breaches. For example, it is quite easy for a random attacker to compromise the web page that passengers use to check-in and, while such an attack won't have any impact on flight operations, the consequences would end up in the media with very dramatic headlines and such news would have a deep effect on passengers' trust in the operator and in aviation. This could cause a loss of confidence, which would lead to a loss of revenues. Without the appropriate cybersecurity measures in place for this evolving threat, the industry may be at risk. Therefore, the industry must maintain the highest levels of confidence in aviation in order to keep growing and to avoid any setback related to cyberattacks [7].

Likewise, ensuring a secure aviation system and staying ahead of evolving cyber threats is a shared responsibility, involving governments, airlines, airports, and manufacturers. It is critical that all of these members adopt a collaborative, risk-informed decision-making model to set goals and define a cybersecurity framework and a roadmap to strengthen the aviation system's resilience against cyberattacks. This roadmap should be driven by a common vision, strategy and different economic from safety-related concerns, and address all security matters including knowledge, prevention, detect, respond, and recover. The industry should also take other successful collaborative government-industry teams as an example for designing aviation cyberspace security solutions, such as the Commercial Aviation Safety Team (CAST) that developed a risk management model to reduce commercial aviation fatalities and initiated new government and industry safety initiatives [8].

In this manner, the cybersecurity framework should be based on common principles such as [8]:

- Establish common cyber standards for aviation systems: organizations such as National Institute of Standards and Technology (NIST), International Organization for Standardization (ISO), and others are working with critical infrastructure providers to develop information security and cyber protection standards for critical infrastructure. Constructive participation in these activities is important to ensuring that aviation's unique requirements are considered when developing the standards.
- Ensure a cybersecurity culture: the same discipline that achieved aviation's high safety standard should also be applied to developing a common vision, common strategy, goals, and definitions, and a common framework and roadmap for addressing the evolving threats.
- Understand the threat: the aviation community should have a common understanding of the actors and their motivations and intents to efficiently plan the defence against them. Adversaries are thinking outside the box to plan cyberattacks and stakeholders should do the same to stop them.
- Understand the risk: to manage cyber risk, the industry must identify the elements of the aviation system that need to be protected. The aviation system is a large and complex international entity with multitudes of stakeholders. It will take time and a disciplined process to understand the interactions of the system and its weaknesses.
- Communicate the threats and assure situational awareness: it is important that government and industry share threat and mitigation data to increase the speed at which threats are mitigated across the aviation system. As aviation cyber threats are also global in nature, there should be mechanisms in place to exchange data with the international aviation community.
- Provide incident response: the aviation community should also understand the timeliness required for responding to threats. Different events dictate different response times. For example, a change to a ticketing system may happen quickly as a software patch, whereas a change to aircraft software requires significantly

more testing, certification, and approvals. Timely processes, methods, and standards for responding to an attack should differentiate the needs of each aviation subsystem.

- Strengthen the defensive system: the industry should also protect the elements of the aviation system with systems and standards. This requires protecting the interfaces between major subsystems as well as the subsystem.
- Define design principles: the design principles underlying the development of the Internet create opportunities for adversaries. As the cyber domain continues to grow, aviation should define design principles for its networks and control systems that consider the evolving cybersecurity threat and ensure no silent failures. This would include identifying architectures and design principles that protect critical systems and platforms against known attack methods and to ensure that aviation systems are secure by default and are resilient against unknown threat scenarios.
- Define operational principles: these principles focus on the operational aspects of systems deployed in the field. This would include a strong cyberculture, operational standards and best practices that mitigate threats in order to ensure resiliency.
- Conduct necessary research and development: the aviation community should focus its resources on researching and developing an appropriate design and operational principles, such as: creating secure and resilient system architectures, including methods for maintaining secure data transfer, isolating critical data, and effectively recovering from attacks; or improving attack detection.
- Ensure that government and industry work together: establish a government and industry framework to coordinate national aviation cybersecurity strategies, policies, and plans. This would include establishing policy for near and long-term cybersecurity development; defining accepted international rules of behaviour; enforcing consequences for bad behaviour, and positioning cybersecurity as a high priority on the diplomatic agenda.

Additionally, recommendations from ICAO Annex 17 (Security) about cyberterrorism should be adopted as a reference to set the cybersecurity framework. For example, it is stated that each Contracting State should, in accordance with the risk assessment carried out by its relevant national authorities, ensure that measures are developed in order to protect critical information and communications technology systems used for civil aviation purposes from interference that may jeopardize the safety of civil aviation. It is also stated that each Contracting State should encourage entities involved with or responsible for the implementation of various aspects of the national civil aviation security programme to identify their critical information and communications technology systems, including threats and vulnerabilities, and develop protective measures to include, security by design, supply chain security, network separation, and remote access control, as appropriate.

In conclusion, the appropriate authority should ensure that there are procedures in place to identify and assess cyber risks to civil aviation. This should include all relevant stakeholders, for example, intelligence agencies, control authorities and industry in that country. Based on that analysis they should ensure that appropriate measures are in place to mitigate the likelihood of those threats occurring, recognize them when they occur and respond to and therefore limit the consequences of such attack [3].

KEY TOPIC T8.4 CYBERSECURITY IN AIRLINERS

T8.4.1 Introduction and Reference Zone

This theme will regard the cybersecurity issue for all European states, not one in particular but will also give an insight into the USA's vision and countermeasures against the attacks.

Civil aviation is the safest transport mode in the world, and it is probably also the most interconnected system of information and communication technology. Cyberattacks are increasing in quantity and sophistication, with points of attack spanning the entire industry chain: new technologies, extension of connectivity, use of Commercial Off The Shelf (COTS) solutions and their ever-quicker integration in the aviation industry (e.g. in the field of Air Traffic

Management) increase the risk and impact of threats to these critical assets, whilst attackers become more numerous, adaptive and far-reaching.

Maintaining the high levels of security in civil aviation therefore urgently requires the development of an effective comprehensive framework addressing all aspects of the aviation system. Regulators, operators and manufacturers have to work together based on a collaborative, risk-based model through a strong framework to address direct threats and at the same time increase the system's resilience against future attacks.

Aviation security = Safeguarding civil aviation against acts of unlawful interference. This objective is achieved by a combination of measures and human and material resources.

In order to ensure the identification of appropriate preventive security measures, the level of threat should be continually reviewed, and risk assessments carried out, taking into account international, national and regional situations and environments.

Whenever a specific threat exists, selected and predetermined preventive security measures should be applied, commensurate with the associated risk assessment, and the nature and severity of the threat.

"Cyber" issue is identified (Figure 8.25) as a new risk for aviation security.

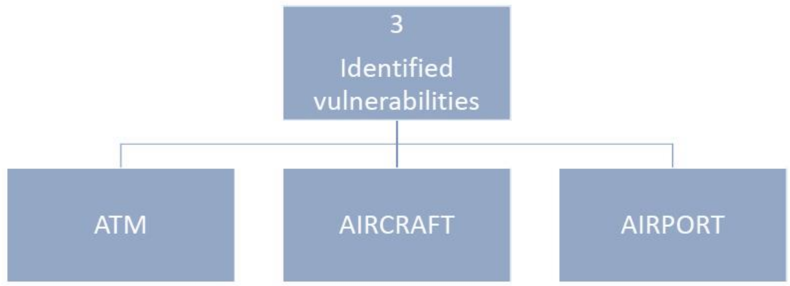


Figure 8.25 – Cyber risks to aviation

T8.4.2 Current Status and Future Prospects

The aviation industry is important to the global economy. In 2013, the air transportation network carried over 48 million tons of freight and over 2.6 billion passengers. Its global economic value was estimated at 2.2 trillion dollars (AIAA, 2013). Any (cyber)-attack in this industry would result in important social and economic consequences.

With the development of new technologies such as the internet, the global aviation industry is subject to a new and growing type of threat coming from cyberspace. As in the other industries, cyber threats purposes are for example the robbery of information, political actions, make a profit, or simply weaken one stakeholder of the industry.

The global aviation industry has many layers overseeing the safety of all the stakeholders involved, from aircraft manufacturers to the passenger boarding a flight. Overall, these different actors can be classified into 4 categories:

- **One international organization**: The International Civil Aviation Organization (ICAO), part of the UN. It codifies the rules of investigation internationally and designs international civil aviation Standards and Recommended Practices in collaboration with its member states.
- **Governments:** national investigation organizations, virtually security agencies that investigate on behalf of countries involved in the accident. France's Bureau d'Enquêtes et d'Analyses (BEA) or the USA's National Transportation Safety Board (NTSB) are the main examples of such organizations. On top of ICAO's

guidelines, they may develop additional safety standards (for example, the NTSB developed smoke detectors in aircraft toilets).

- **Trade organization of airlines**: International Air Transport Association (IATA) oversees standards at the industry level and is directly in contact with most of the world's airlines.
- **Manufacturers of aircraft and security systems**: many large corporations such as Boeing, Airbus, Dassault, Thales, Honeywell… They constantly update their systems to face new threats with the advice of the different boards described above.

Because of its complexity and its weight in the economy, breaking the aviation industry's security constitutes a great challenge for hackers and terrorists. Moreover, this industry relies more and more on information and communication technology (ICT). As an industry that is well known for providing the safest type of transportation, it is mandatory for all its stakeholders to understand the risks and to prevent any malicious events for the good of the industry, the economy, the population and the environment.

Online attacks are on the rise resulting in headline-grabbing stories. In the last few years, we have witnessed data breaches across multiple industries including banking, retail, health insurance, and online-only businesses. The financial impact alone is staggering. Inevitably, cyber threats will continue to grow in number, cost, and sophistication. Consider the greatly expanded use of cloud and mobile devices. Businesses are embracing these tools to connect their internal staff and operations. They are also accelerating usage to connect externally—with strategic partners, customers, and a multitude of other third parties. These efforts are serving to enhance efficiencies, collaborations, and competitiveness. But along with these benefits, new vulnerabilities have emerged. Mobile devices create more entry points for hackers by dispersing data. The cloud, where data are aggregated, makes data more accessible. And these sources of risk are continuing to expand quickly. To mitigate the threats, companies will need to reassess all facets of their business and establish internal protocols to effectively manage them. Furthermore, as businesses aggregate and analyse more data on customers and processes, the data become increasingly valuable and a more attractive target for hackers. This double-edged sword applies to technology as well. While improved technology allows businesses to better understand and target their customers, advances in technology also provide hackers with more sophisticated technology with which to perpetrate attacks.

For the airline industry, cybersecurity risk is top of mind. According to our survey, 85 percent of airline CEOs expressed concern about this risk versus 61 percent of CEOs in other industries, a difference of 24 percentage points. As in other industries, airlines are concerned with the theft of sensitive customer or company data. But an added threat for airlines is that technology is being used to improve the connectivity of flight operations systems with ground crews and air traffic systems. While this enhanced communication and integration is essential to the improvement of financial and operational performance, it does provide more opportunities for those seeking to exploit these advances. So as airlines increasingly adopt advanced technologies, they must also upgrade security procedures to allow for safe innovation. Overall, security procedures to date have been effective, safely integrating the many technological advances introduced to aircraft and airlines. Yet the industry continues to see major technological advances that contribute to the complexity of protecting data and assets. Two of these are tablet-based electronic flight bags (EFBs) and the installation of in-flight entertainment and Wi-Fi connectivity systems (IFEC). EFBs are particularly popular with pilots as they have taken the place of heavy binders that pilots used to carry onboard. Yet a recent survey revealed that many airlines do not have a targeted plan in place to safeguard the security of EFBs. On-board IFEC systems are proliferating. Currently, they are physically segregated from cockpit systems.

Nevertheless, these systems greatly increase the number of connections, vendors, and technologies involved, which in turn creates more hacking opportunities. The threats posed by EFBs and IFECs need to be managed holistically, with airlines closely cooperating with other carriers, hardware and software providers, aircraft OEMs, and other industry stakeholders. Another potential cyber issue for the airline industry is the Federal Aviation Administration's (FAA) modernization of air traffic control, notably the Next Generation Air Transportation System or NextGen. The current system is 40 years old and relies on radar, which provides limited connectivity. NextGen seeks to improve network efficiency by using GPS (global positioning system) that is software-based and connected to the Internet.

While it's widely accepted that this transition is needed to modernize our air traffic control systems, the General Accounting Office has voiced concern that implementing a system with Internet connectivity brings with it greater threats to security.

As real-time aircraft connectivity continues to evolve, providing information where and when it's needed to optimize airline operations and the customer experience, it not only increases the number of opportunities for attacks, it potentially makes them more damaging. The industry is making significant investments and taking important steps to address cybersecurity, calling for increased oversight from boards of directors as well as third-party providers. The FAA has "convened a private meeting" to examine the security of aircraft systems, which at the very least is an acknowledgement of the need for industry-wide approaches and standards. Tony Tyler, the head of the International Air Transport Association, or IATA, has publicly stated that regulators have to work with airlines to develop a global security system that adopts "an end-to-end risk-based approach." IATA's position is that the industry can effectively deal with most attacks by focusing efforts on prioritizing and allocating resources to protect the airlines' most valuable assets.

In the interim, without any uniform industry standards in place, each airline has to consider how to reduce the risk of a cyber-attack and how to deal with one when it happens. Regardless of how a cybersecurity strategy is formulated, the airline's board has to support the strategy and ensure that it is coordinated across all departments in the organization. A cybersecurity strategy includes methods to prevent, detect, and react to attacks as well as a mechanism for capturing learnings. Feedback collected at each stage should be incorporated into the overall security program to make attacks more difficult to execute successfully. While prevention methods are not fool proof, an airline's first security goal is to try and stop attacks from occurring, both on the ground and in the air. Once an attack occurs, airlines must detect the attack as quickly as possible and isolate the intrusion. And then airlines must react quickly and efficiently to minimize the damage and reduce the risk of future incidents. As we have seen in many industries, this involves extensive analysis of the potential vulnerabilities across an organization's internal operations, supply chain, and strategic partner network.

The United States of America have a firm opinion related:

"America must also face the rapidly growing threat from cyber-attacks...our enemies are also seeking the ability to sabotage our power grid, our financial institutions and our air traffic control systems. We cannot look back years from now and wonder why we did nothing in the face of real threats to our security and our economy." - President Obama, 2013 State of the Union Address

All the developed countries around the globe are seeking a strong collaboration and are committed to developing a synergy to protect against cyber-attacks and protect their assets.

T8.4.3 Evolutionary Progress. Predictions

What constitutes an effective defence plan? There are several key elements: Oversight at the board level and building a security culture

A cybersecurity program has to rest on a risk-based framework that addresses risks across the airline including back-office IT, maintenance, operations, and consumer-facing systems because failure in one area can affect others. Management, employees and the board must become more cyber aware as breaches can occur as a result of small lapses in procedure. But security awareness training is not enough. Airlines need to incorporate cyber awareness into the security culture, embedding cybersecurity into the organizational fabric. Below are specific examples of the roles various functions need to play:

- Procurement: looks for the counterfeit parts that may have come unwittingly from providers
- Maintenance: considers the security maturity of MRO partners and potential points of ingress;

- Operations: considers enhanced digital security measures needed to fly safely to high-risk destinations;
- Marketing: examines the value of consumer information and guards against identity theft and exploitation of awards programs;
- Information technology: modernizes infrastructure and implements security monitoring and remediation protocols that establish resiliency for flight operations;
- Management: sets the tone at the top and appropriately communicates to the broader enterprise and its trading partners;
- Board: ensures operational cyber risk is put in the context of other carrier risks and is properly resourced.

Proactive approach that sets priorities

Since it's too expensive to protect all assets from all threats, airlines need to prioritize—assets, threats, and threat perpetrators. On assets, they must recognize their protection obligations, identify associated digital assets, and focus aggressively on protecting those assets most valuable and critical to the organization. On threats, airlines need to prioritize and categorize the kinds of threats they are facing, both those known currently and those projected to emerge over the next few years and recognize the signs of an attack early on. On perpetrators, they need to look at the most threatening players, a list which can include nation-states, organized crime, and terrorists.

Airlines cannot do this by themselves: the risks are too numerous and diverse—and constantly changing. They need to avail themselves of all existing tools, public and private, that can help mitigate risk. In the United States, the NIST Cybersecurity Framework supports businesses in critical infrastructure industries including transportation. In addition, the Department of Homeland Security established the Critical Infrastructure Partnership Advisory Council (CIPAC) for aviation as a public-private partnership to address the cyber risks affecting the industry. To augment this industry sector insight with carrier-specific threats, many airlines subscribe to threat intelligence services that inform them about the latest threats. Airlines then can model different scenarios to determine optimal prevention approaches. Real-time feeds from these services are fed into security operations procedures so they can be dealt with. Many carriers are also harnessing the power of the cloud and big data to model and monitor evolving and new cybersecurity threats. Using these new technologies allows airlines to scale protection efforts across their organization and increase the sensitivity of their prevention programs. Additionally, some companies perform periodic penetration assessments. These are generally commissioned by senior management to evaluate the strength of security and monitoring procedures.

Support international standards

There are no international standards for cybersecurity design and testing, which is widely acknowledged to be an issue. The US, Europe, and the International Air Transport Association (IATA), a trade association of the world's airlines, have begun initiatives to address the lack of standards. Last year, the US Federal Aviation Administration, or FAA, established a new industry working group to provide guidance on how to improve cybersecurity on e-enabled aircraft. The European Aviation Safety Agency (EASA) held a workshop to address cybersecurity. IATA has also called for better sharing of airline cyber threats among governments and airlines worldwide and asked governments around the world to take a more active stance in improving cybersecurity. Airlines can do their part by supporting efforts to build international standards. While industry associations establish standards, airline Chief Information Security Officers (CISO) could form informal alliances to discuss leading practices in the industry and how best to implement those practices. These peer-to-peer interactions can lead to focused discussions on specific threat areas.

Address supply chain risks

It is critical that airlines and their external partners (such as OEMs, MROs, IFEC [in-flight entertainment and communications] providers) collaborate on threats and response techniques to share best practices to increase the knowledge base. But, in addition, airlines have to monitor partners' operations for potential security breaches and manage the access of users to different systems. In particular, smaller companies tend to have less stringent security protocols and invest less than their larger counterparts in security measures. To mitigate risk, airlines have to ensure their vendor contracts include audit clauses and specified testing procedures.

Cybersecurity capabilities. Beyond these broad strategic approaches to cybersecurity, airlines need to consider the technologies and processes that can strengthen their programs to deal with today's threats. Some of those tools are described below:

Threat intelligence

Airlines must gather both external and internal threat intelligence from multiple sources including third-party vendors, subscription feeds, and agencies as well as system event and log information. This information can then be correlated and fed into a 24 x 7 x 365 security operations centre (SOC) to help identify and prioritize threats. It's also key that airlines get involved at an industry level, so they can raise awareness of threats among colleagues. One such organization, the Aviation Information Sharing and Analysis Centre (A-ISAC), helps constituents better prepare for and manage sector-specific threats, vulnerabilities, and incidents. Other organizations that can provide intelligence include federal agencies, such as the FBI and the Secret Service, and industry consortiums, such as ISACA (Information Systems Audit and Control Association) and CERTs (Community Emergency Readiness Teams).

Identity and access management

Identity and access management (IAM) is often overlooked as a legacy capability, yet it provides a suite of functionality that authenticates and authorizes employees, partners, and customers to access airline applications and systems. IAM systems may cover many functions: eCommerce, ticket purchase, loyalty redemption information, and concourse applications to generate boarding passes, and also enable collaboration between airlines and governmental agencies, such as the Department of Homeland Security, and communication with MRO partners. There are a few capabilities within IAM. One is privileged access management (PAM) that is meant to protect against the use of generic and shared IDs. The system includes capabilities for enforcing, controlling, and managing privileged access to systems; logging, monitoring, auditing, and certifying privileged access; and reporting violations. Another variation is multifactor authentication (MFA), which has been adopted by leading airlines that have moved beyond a 'passwords only' approach. It requires more than one method of authentication from independent categories of credentials to verify a user's identity and is usually comprised of something you know (e.g., password), something you have (e.g., token) and something you are (e.g., biometric). MFAAs restrict access to an airline's Internet and employee portals as well as key enterprise systems. Adaptive authentication solutions add an additional layer of security. They assess the risk associated with each authentication attempt/transaction by requesting additional attributes that help to verify identity. With basic password authentication, systems are vulnerable to attackers exploiting credentials that were compromised elsewhere.

In the airline industry, several carriers have been hit with millions of dollars in fraud-related to unauthorized redemption of miles and points by rogue attackers. The full value of adaptive authentication comes from establishing normal behavioural patterns of users and populations and then detecting anomalies by applying contextual data about the user, endpoint, transaction, or asset to make a risk-based authorization decision (e.g., logging in from a new geographic location).

Data protection/encryption

Leading airlines use encryption and tokenization technologies to help protect customer and employee information, including payment cards, national IDs, passport numbers, and bank accounts. This is particularly critical in today's digital environment with the widespread use of social media and online applications. One example of a dynamic regulatory environment recently, the European Commission proposed changes to its privacy laws to strengthen and unify data protection for individuals in the EU. It also addresses the export of personal data outside the EU. More importantly, it stated that the penalties and fines for the most egregious violations could be up to four percent of an organization's revenue.

Design/application security

Leading airlines are embedding security requirements from the 'ground-up' and not as an afterthought, starting with the design of secure applications and products. According to NIST, it is 6.5 times more expensive to find and address an application flaw in development than during design, 15 times more expensive during testing, and 100 times more expensive during production. In the past, efforts may have been limited to regulated or commercial applications that were in scope for SOX 404 or the payment card industry (PCI). However, this left mission-critical operational systems for ground and aircraft operations as well as MROs and other third parties out of scope for security. The threat landscape that airlines face has moved beyond the theft of data such as payment cards and towards the operational resiliency and integrity of all systems. Furthermore, any products and services that are developed for the crew, ground operations, and customers must consider security as a key functional requirement in today's landscape.

Security awareness

Whether it's the tampering of concourse devices, activity within the cabin (e.g., plugging into USB ports), or corporate espionage, awareness is often the front-line defence against threats. All airline employees, not just the physical and information security departments, have to share in that awareness and understand their roles and responsibilities in preventing cyber-attacks. A good analogy for the depth of cultural integration required is the way that environmental safety regulations have become ingrained in the factory culture. For example, workers understand they need to wear certain footwear on a production floor for safety reasons and would almost certainly stop someone from wearing open-toed sandals. In the factory, policy and heightened awareness have been woven into the fabric of the culture through tone at the top, organizational campaigns, and incentives as well as penalties. A similar cultural commitment is needed on the cyber front. For example, phishing attacks are still one of the most effective attack vectors used by adversaries; they are very easy to exploit and can yield significant returns even if just one target takes the bait. In such an attack, an employee is targeted to open an email link, which then downloads malware that infects the IT environment of the entire organization. Recently, executives have been the target of these types of attack because of their access to sensitive data. It is easy to see how one unwitting employee or executive can lead to significant damage.

T8.4.4 Identification of Gaps

When dealing with a cyber incident, organizations often discover that there were signs of an intrusion long before the breach was identified. In our experience, advanced threat actors often maintain remote access to the target environment for 6-18 months before being detected. During this time, an attacker has the opportunity to identify critical systems, locate valuable data, and execute the most devastating attacks. Early detection, along with a clearly defined set of operational processes to quickly address an attack, is vital to reducing the consequences. This is true for all industries, including the airlines.

The objectives of today's advanced cyber threats are typical to steal desired data and maintain access to the environment for as long as possible. Over the past decade, in all industry sectors, cyber intrusion activity targeting multinational companies has increased significantly. Any company with proprietary data perceived to be of economic value—or involved with national security and critical infrastructure, such as aviation—has increased from a potential to a likely target.

When compromised organizations conduct incident post-mortem analyses, they usually discover that their monitoring processes and tools are lacking. They may not have a holistic view of systems and data across the enterprise and they may not include needed alerts, rules, and workflow to detect or communicate threat scenarios. In fact, we see that many current tools only perform basic pattern matching and counting and fail to correlate data across multiple systems and between seemingly disconnected events.

Part of the challenge of detecting security breaches is keeping up with the constantly evolving set of threat actors, targets, and vectors. Detection protocols have to be one step ahead of the latest hacking techniques. Another problem is that while external threats get more play in news headlines, insider threats can be much more difficult to diagnose and costly to remediate.

Companies also face a financial challenge: When it comes to cyber strategy, it is often more difficult to obtain funding for detection efforts than for prevention. Preventative measures, such as encryption and access control, are often tangible and, as a result, easier for management and employees to understand and support.

Detection, on the other hand, is a moving target with generally unknown actors, uncertain penetrations, and unpredictable timing. Since attacks are so varied, it can be hard to build a leading-edge detection system. Airlines face an additional burden in that they have extensive third-party networks. And for all industries, there is little concrete regulatory guidance other than the International Organization for Standardization (ISO) and the National Institute of Standards and Technology (NIST).

Include detection in cyber programs

The leading airlines that include detection as part of their cyber programs have built comprehensive coverage of their network, data, and endpoints (Figure 8.26). They are able to react so quickly to attacks that response times are virtually instantaneous. This ability to move decisively and swiftly not just limits losses, but also prevents the intruder from temporarily pausing the attack and hiding elsewhere in the enterprise's networks only to attack differently at a later date.

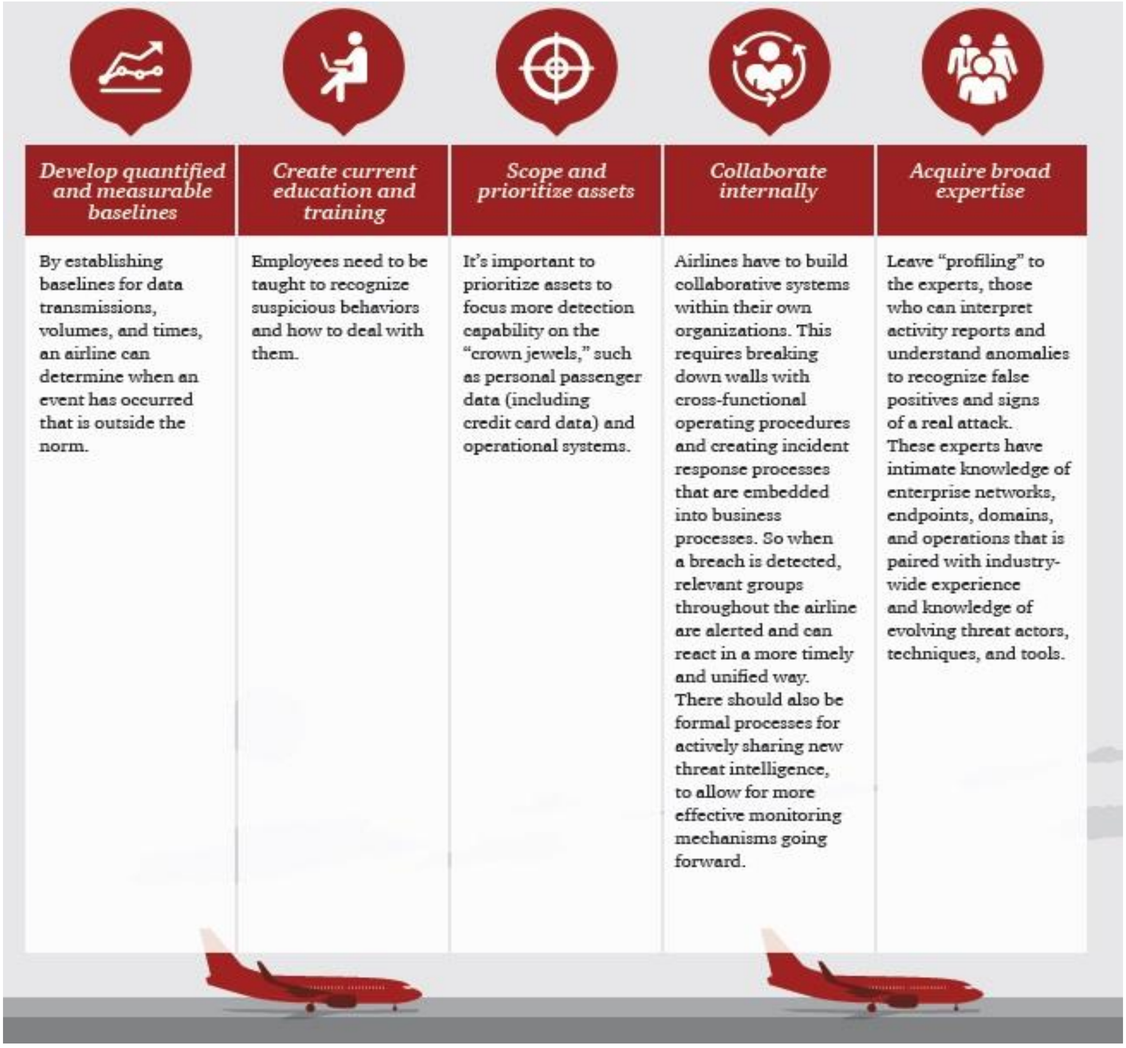


Figure 8.26 – Measures against cyberattack

While cyber detection has to be tailored to meet the specific needs of each airline, these tools cannot simply log and aggregate data points—they have to intelligently correlate the data to identify an intrusion (Figure 8.27). In addition, next-generation cybersecurity defence programs include other essential capabilities such as those discussed below:

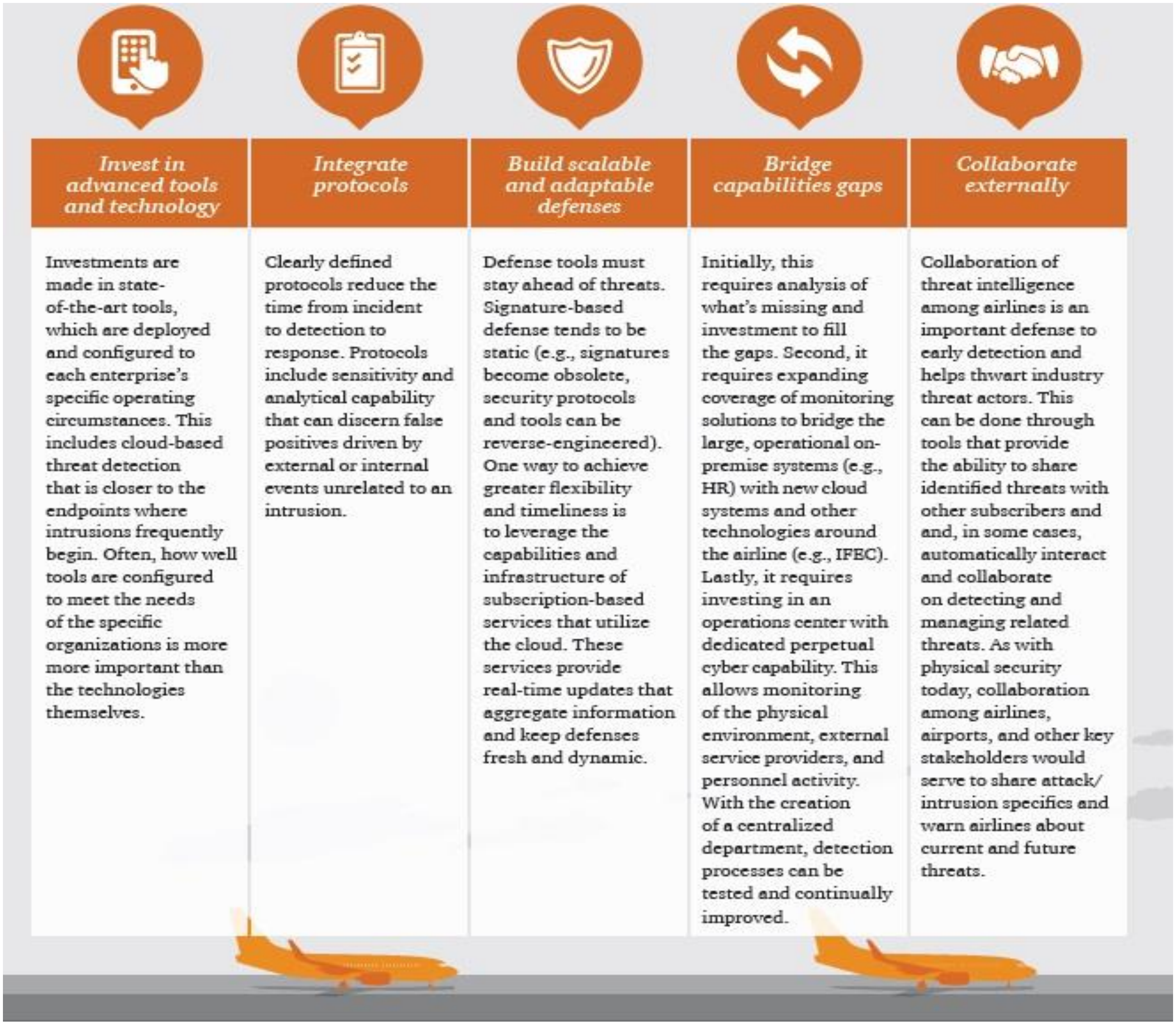


Figure 8.27 – Further measures against cyberattack

***Companies in the aviation industry face yet another challenge*.** A key trend is increasing interconnectedness, whether it's between aircraft and ground control stations, airlines, airports and other aviation stakeholders, or between dispersed field-deployed assets. This same interconnectedness that provides operational efficiencies simultaneously introduces further risk to commercial passenger airlines. From billing and reservation systems to aircraft engine telemetry, aviation companies have broad networks that not only provide multiple high-value targets for attackers but because of their interconnections open up multiple avenues of penetration into an airline's core systems. A recent example of the danger inherent in interconnections with third parties occurred in the attack on an organization's air-conditioning vendor, which then allowed hackers to penetrate the corporate network. While there's no going back on interconnectedness—it is a factor in today's world—every airline has to address the risk of third-party networking and the potential weakness of points of intersection.

Compounding the challenge of implementing and maintaining an effective cyber detection program are the many seismic changes in the airline industry in recent years that add to complexity (Figure 8.28). Below are some changes we have seen that alter the way airlines operate and make it more difficult to detect cyber threats:

- Growth in the volume and types of data created by new-model airframes, engines, and components;
- Increased focus on capturing, mining, and using passenger shopping and travel preferences and behaviours;
- Proliferation of increasingly advanced and interconnected assets among aircraft, airports, airline network operations and dispatch, and other stakeholders in the travel ecosystem;
- Increased dispersion of data collection points, geographically and physically;

- Increase in the number of vendors that tap into and use airline data to improve operations, passenger management, and other core airline functions;
- Reliance on potentially insecure legacy applications and platforms that support core aircraft operational activity.

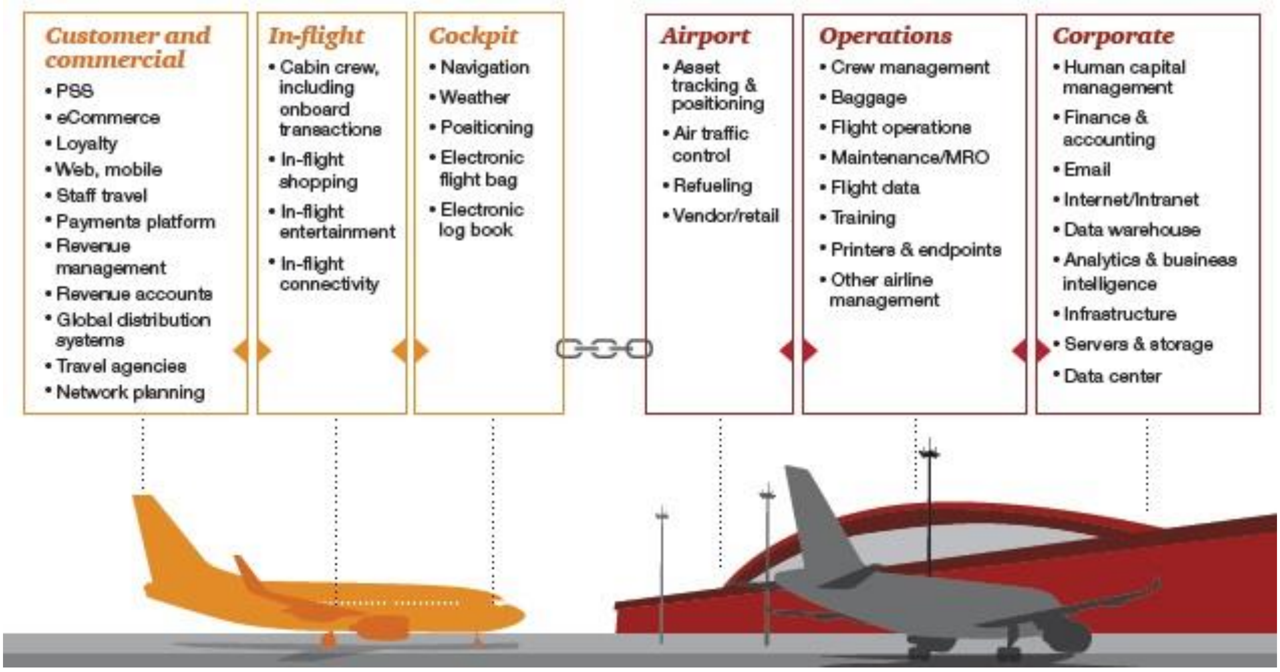


Figure 8.28 – Data Streams vulnerable to cyberattack

Since airlines can pay a particularly heavy toll for not having effective cyber detection tools, they have become much more proactive in developing tools as part of their cyber programs. According to the latest Airline IT Trends Survey from SITA[2], 91 percent of airlines are planning to invest in cyber programs over the next three years, up from 47 percent in 2013. The study also shows a large increase in the number of airlines that think they are prepared for the common types of cyber threats: 48 percent compared with 17 percent three years ago.

T8.4.5 Current Status of Relevant Technologies

Efforts have been made but not enough

As seen in the previous section, it is important to consider the rise of software complexity in the aviation sector. Indeed, software complexity is increasing, and software security cannot be totally guaranteed. This is the reason why it is important to handle vulnerabilities in this sector, to deploy software updates to prevent any attacks and of course to regularly test the security of critical systems.

With the complexity and the high number of stakeholders in this industry, the number and the origins of breaches could be substantial. In the same way, establishing the stakeholder accountable for a breach or an attack could be difficult. Some previous cases in the aviation sector have led to some observations. For example:

- When a vulnerability or a breach is discovered, vendors do not always address or fix it
- No stakeholder would accept to be accountable for a breach or a vulnerability: the suppliers blame each other, the main manufacturers such as Airbus or Boeing blame the suppliers, the airplane operators blame the manufacturers and so on
- Critical systems and cabin systems on airplanes are not isolated properly from external threats
- The principal internal communication protocol, Avionics Full DupleX (AFXD), had poor security solutions implemented

As cyber-attacks against the aviation industry have increased considerably, setting cybersecurity as a major concern, all 4 categories of industry stakeholders as pointed out earlier worked together to address these cyber threats.

The major efforts made by these stakeholders are the following:

- With the increase of cyber-attacks in all the industries and the increase of computer-based solutions used, ICAO encourages better and stronger collaboration between all the stakeholders to identify as many threats and risks as possible (Lim, 2014);
- ICAO organized a discussion to define responsibilities on cybersecurity for the aviation industry;
- ICAO would like to encourage countries to implement a strong cybersecurity strategy and management. The goal is to implement more policies and measures to prevent any cyber-attacks that could lead to dramatic consequences. This recommendation by the ICAO includes crisis management and business resilience;
- More and more countries started to work on cybersecurity a few years ago;
- More and more airports started to implement measures to secure any IT systems already exposed. They also started to consider upstream the cybersecurity issues for future projects;
- With safety as a top priority, IATA conducts yearly audits mandated by governments and provides airlines with a cyber-security toolkit that has a traditional risk assessment approach (IATA, 2015).

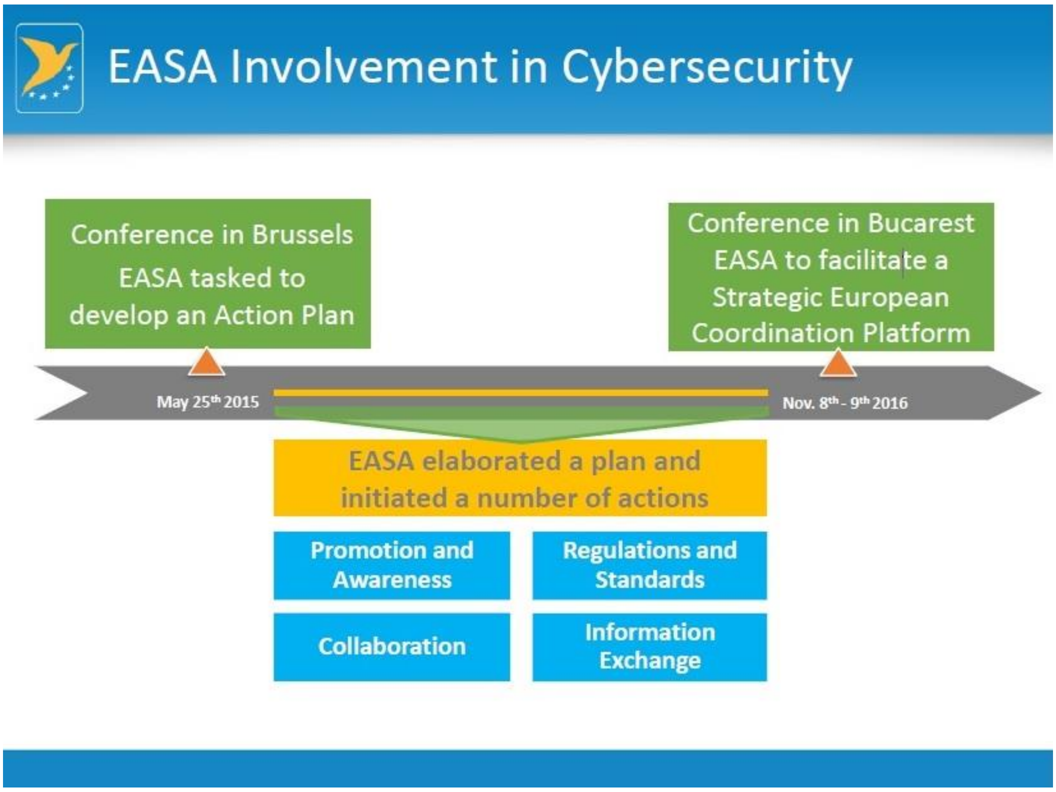


Figure 8.29 – Example of an initiative on cybersecurity

- Finally, manufacturers have made some efforts as well: Boeing implemented additional security measures on the 777 aircraft to prevent onboard hacking of critical computer systems (Federal Register, 2013).

Cybersecurity initiatives are taken by various organizations, e.g. EASA (Figure 8.30). A good example of cross-stakeholder collaboration is the National Transportation Safety Board, the US government agency that investigates and provides recommendations on accidents that occurred in all forms of transportation. The processes in place in this agency are "more focused on figuring out what went wrong than in laying blame or assigning liability" and takes into account the perspective of all stakeholders involved in the accident to make conclusions. Many experts in the US have been recommending that the government develops a similar agency with a focus on cybersecurity in transportation, a quest that may have found its answer in the 2016 Cybersecurity standards for aircraft to improve resilience act, or the Cyber AIR act (Wolff, 2016).

Although a lot of efforts have been made, there still exist a lot of issues to be addressed (Figure 8.30).

Figure 8.30 – Future initiatives on cybersecurity

T8.4.6 Advantages and Limitations

Cyber Security Challenges for the Aviation Industry

As the aviation industry is known for providing the safest types of transportation, the stakeholder must consider seriously the cyber threats if they want to preserve the efficiency, security and resilience of their systems. Moreover, underestimating these new types of threats would lead to a drop in the number of users as people would are looking for a safe transportation network. To deal with these threats and to maintain a high degree of confidence, stakeholders would need to continue the efforts made to date.

To strengthen its cybersecurity, the aviation industry could consider some of the propositions made by experts and agencies globally. The following suggestions seem to be the most appropriate:

The aviation industry has to evolve and to introduce strong systematic tests against cyber threats in addition to the compliance testing already implemented. The latter does not imply security and is managed internally by experts in compliance and availability testing. Internal security testing is then disregarded because of internal constraints and a lack of expertise. It is more than important to test all the components independently and the complete systems by external experts. These experts would have the advantage to be independent, less constrained, unbiased, creative, and more than anything else expert in breaking systems.

- The aviation industry is made up of traditional isolated systems that are more and more connected and exposed (AIAA, 2013). Like in other industries, for any project it is important to:
    - Assess the needs and the allowance for these external links;
    - Ensure that security processes are implemented;
    - Ensure that vulnerabilities can be addressed quickly;
    - Be aware that security updates might break the current certification. The choice of exposing and connect isolated systems implies to consider a new environment.
- Critical systems should be tested by external and independent companies that have real expertise in cybersecurity.
- Provide high security for critical communication systems such as the radio. This security should ensure strong authentication, confidentiality, integrity, and availability. Any other unprotected communication systems should be considered as potentially compromised. Finally, it is important to check that critical and non-critical systems are isolated.
- Any company in the aviation industry should raise awareness among all the employees on the importance of considering seriously cyber threats. It is important to set up a real cybersecurity culture in the critical entities of this industry.
- Every company in the aviation industry should assess its needs in term of cybersecurity. These companies should be aware of their vulnerabilities and implement some measures to reduce them. Like any other industry, the aviation sector should consider seriously cybersecurity like they do for HR, Finance, operations and so on. The companies of this industry should have a deep understanding of the threats and the risks. Who are the attackers? What are their motivations? How will they attack? What should be protected in priority?
- Implement stronger internal policies and plans within the company. Indeed, as companies rely more and more on computer-based systems, interact more and more with other companies or people such as passengers, it is mandatory to strengthen internal policies and plans.
- It would be important to also implement a recovery plan and to increase resilience.
- Governments should set up some regulations and norms in term of cybersecurity.

All these recommendations might be already implemented today but it is interesting to note that they are shared with the other industries. The aviation industry might be more cyber-secure nowadays, it should continue to strengthen its systems as technologies evolve constantly, so do the threats.

T8.4.7 Proactive Measures

Airlines have long had to deal with many operational disruptions, such as unplanned aircraft maintenance, adverse weather, business system faults, and other unplanned events that cause delays and cancellations. The need to address issues that impede day-to-day operations can push aside other types of threats, especially cyber-related ones, which may appear at first glance to be innocuous. However, even a relatively low-impact attack may indicate a vulnerability that can lead to a more serious and expansive intrusion.

A clear indication that incident response processes are not working is that very few (or no) attacks are detected. Highly mature, global organizations should expect to see hundreds of successful (not blocked at the firewall nor remediated by antivirus software) low-impact attacks in a year and, perhaps, dozens of more serious attacks annually.

How can an airline create an effective cybersecurity incident response plan?

Define Parameters and Protocols

Many organizations are uncertain about how to define a cyber incident, how to respond, and how to measure potential impact. This creates a dangerous opening. If an enterprise fails to mount an effective reaction to an incident, an intruder has time to penetrate more deeply into the organization's network and cause greater harm. With detection time averages 6-18 months, the slow reaction has become a widespread problem.

Airlines are no different from other organizations: All cyber incidents must be contained and mitigated as quickly as possible. But not every incident requires a full-court press. It is essential to implement a framework for categorizing the severity of an attack and its potential impact on the organization. IT and cybersecurity professionals should develop a matrix that labels attacks on a graduated scale such as high, medium, and low impact. The matrix should specify financial exposure, number and type of systems involved, and a clear plan for which stakeholders, internally and externally, should be notified.

For example, the matrix should define when the CIO must be notified, or under what circumstances the legal team must be notified. In that way, the right leadership will be alerted at the right time and for the appropriate level of risk. Often, this kind of clear protocol can prevent a small problem from becoming much larger and ensure that large problems get the attention they require as quickly and efficiently as possible.

Not everyone in the organization needs to be made aware of every incident. In fact, an effective incident response process can limit the number of people involved. Different triage protocols should be considered for major/minor incidents, including notifying the appropriate business units, enacting (or not) a crisis public relations strategy, and coordinating notification efforts. Generally, the most severe incidents should receive the widest coverage, which can run counter to an organization's tendency to de-emphasize such incidents.

The vast majority of incidents tend to be of very low severity. However, airlines need to establish regular metrics around these incidents. By identifying, documenting, and analysing low-risk vulnerabilities, senior leaders may come to see that a particular intrusion type or exploited vulnerability is having a broader negative impact on the organization than previously understood. Metrics help establish patterns that can be more useful than just viewing incidents in isolation and highlight new opportunities for improvement, cost savings, and risk reduction.

Create response structures

Large organizations tend to have three distinct types of incident response structures. One, the primary focus of IT operations, involves information technology incidents, where the breakdown of some portion of the IT eco-system creates a potential business impact. The second structure is centred on crisis management incident response to deal with natural disasters or other events that can cause major disruption. The third structure concerns cyber incident response processes. These structures should work together to ensure that all incidents are captured.

Some airlines use their IT operations incident framework for cybersecurity incidents. However, IT operations cannot adequately address the severity of a cyber incident because it focuses on glitches in IT systems. In a cyber incident, all IT systems could be functioning while millions of customer records are being exfiltrated for further exploitation. For that reason, it's important to develop an incident severity matrix/framework that takes into account the possibility that standard IT processes may appear to be operating normally although an attack is in progress.

Establish regional capabilities

For airlines that have a global footprint, allocating and integrating resources from global geographic regions is an important part of the cybersecurity incident response plan. It's unrealistic to expect a team in the US to fully counter a threat in Asia. In many cases, criminal groups wait to launch their most devastating attacks when an organization has the fewest people available to deal with it; or when they have the greatest chance of blending in with business-as-usual operations. With timeliness often a critical factor in incident response protocols, airlines should incorporate regional capabilities to deal with incidents promptly.

Develop the three-legged stool

Successful cyberattacks are not just an IT problem, they are a business problem that requires a holistic corporate response. Three of the most common stakeholder groups in an incident response plan include (Figure 8.31) information or cybersecurity, legal, and corporate communications. While there can be additional groups involved in an incident response plan, any serious plan has to involve strong, focused participation from a core team. A best practice is to form a working group with permanent representatives from these three groups who are responsible for creating, reviewing, updating, and incorporating lessons learned from cyber incidents.

When an incident occurs, a single leader should be appointed from one of the three core groups to serve as the focal point of the response. Generally, in highly mature organizations, information security is the first to recognize an incident and leads the initial response. If the immediate technical impact is quickly mitigated, continuing activities may focus on legal liability. At that point, leadership is likely to shift from information security to legal. That shift should be explicitly noted by the larger team so that the role of a leader is always clear to those involved. The lack of a single leader can lead to confusion, delay, and disconnected communications among team members, resulting in increased risk.

Figure 8.31 – Departments involved in cybersecurity

Adequately fund and staff

There is often a large level of investment in prevention activities and technology, but considerably less in detection and response. As a result, these functions are often understaffed, or staffed without the appropriate skill sets. Large organizations should create at least one position dedicated to incident response who has the requisite talent and experience. This is a particularly critical role in the airline industry, given the various threat vectors an attacker can take, and the potentially high stakes of an incident.

Even with a dedicated incident response role, organizations generally have to rely on third-party retainer services for specialized capabilities, such as cyber forensics and breach investigation support. These third parties need to be integrated into an organization's cyber program to ensure that, as third-party resources change, new team members are familiar with the organization's history and practices.

Simulate and practice

Airlines can use simulation exercises to help them prepare for cyber incidents by walking through plans and procedures. These exercises can serve as part of a broader strategy for practising how to move swiftly and effectively in response to an attack. Typical simulations include working through the severity matrix (minor, serious, and major incidents) and proper notifications; collecting forensic data to help determine the nature of the event; coordinating communications, including the groups that are part of the three-legged stool; and discussing backup plans and restoring actions.

Capture lessons learned… and apply them

Once an incident is dealt with, the natural tendency is to move on by the organization. But leading organizations have a structured lessons-learned process that allows them time to review and update protocols and tactics: What went well? What did not? How can efforts be improved? What specific actions should be taken and by whom? The answers to these questions help strengthen prevention strategies and lead to an improvement in airline cybersecurity.

To illustrate this further, consider that cybersecurity was not a concern when airline legacy systems were established. As a result, these core business systems can present significant vulnerabilities; many possess high-value data but do not have the safeguards in place to defend against modern threat techniques and technologies. But as legacy systems are upgraded or replaced, airlines can simultaneously incorporate new security measures.

As airlines become increasingly connected across internal operations and with their supply chains, creating a more open environment, it increases the probability that information will be compromised. If that occurs, an airline has to look for points of possible entry and close the loopholes—actions that are increasingly hard to do as system architectures integrate more and more new technologies and systems with existing legacy mainframes that are too entrenched to replace. Not only can these disparate systems be attacked, but the integration points themselves create other vulnerabilities.

To close the loopholes, airlines must "capture" and then "apply" learnings. Often, "apply" is much more difficult to execute than "capture." One way to deal with this problem is to incorporate learning into a metrics program. By tracking and implementing specific improvements identified during lessons-learned, an airline can build a body of knowledge to help it deal with the next incident.

Report threats

While airlines are primarily concerned with their own security, they recognize they are part of a larger aviation ecosystem. This community can play a critical role in providing a countervailing force against organized cyber hacking. If an attack is successful in penetrating one airline, the same kind of attack is likely to be used (or is simultaneously being used) against other airlines.

The aviation industry has an organization dedicated to the sharing of threat information and response and recovery coordination known as A-ISAC (Aviation Information Sharing and Analysis Centre). The ISAC network was established by the US government to help support and protect private-sector organizations that are part of the country's critical infrastructure. In an ISAC, members can share information anonymously for the mutual benefit of their industry. This proactive sharing helps airlines understand the current threat environment and identify and respond to attacks.

To date, most of the threats to the airline industry have focused on obtaining customer data. However, airlines have also been subject to attacks on corporate information, physical systems, and operational disruption. According to an official at the European Aviation Safety Agency (EASA), aviation systems were subject to approximately 1,000 attacks each month. Ransomware attacks are becoming much more frequent. Criminal organizations are placing an enormous burden on all legitimate businesses competing in the global environment. With the increasing and expanding threats to airlines and aviation, a key way to blunt their effectiveness is to share information with other members of the industry, forming a collective mechanism for self-defence (Figure 8.32).

Examples

The intentions exist among hackers and the attacks happen.

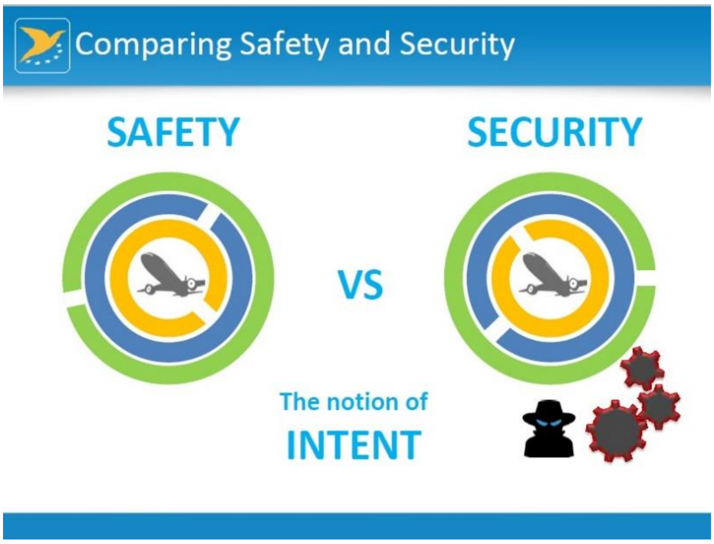


Figure 8.32 – Intent in safety and security

Miami International (MIA) – 20.000 hack attempts per day

LA Area Airports:

- 2.900.000 hacking attempts in one year;
- 60.000 cases of internet misuse;
- Attacks on network baggage systems via malware.

➢ In June 2015, a Polish aircraft with hundreds of passengers aboard was grounded at the Warsaw airport for about five hours. Airline officials believe it was likely caused by a Distributed Denial of Service (DDoS) attack. In this kind of attack, an organization's system becomes overloaded by a flood of communication requests, so that it can no longer carry out normal functions.

➢ In a 2015 report, the Government Accountability Office (GAO) called for the Federal Aviation Administration to develop "a more comprehensive approach to address cybersecurity" as it embraces next-generation technology.

➢ Aviation Administration to develop "a more comprehensive approach to address cybersecurity" as it embraces next-generation technology. The GAO noted that the aviation regulatory agency had adopted measures to protect its air-traffic control system from cyber intruders (Figure 8.33). However, it stated that "significant security-control weaknesses remain that threaten the agency's ability to ensure the safe and uninterrupted operation of the national airspace system."

➢ The non-profit Centre for Internet Security (CIS) reported a few years ago that 75 US airports were impacted by an Advanced Persistent Threat (APT) attack, including two where the computer systems were compromised. APT hackers are foreign groups with the resources of a nation-state or other large organization behind them. The CIS said it issued a cyber alert to its members after identifying phishing emails and certain kinds of suspicious network traffic.

Figure 8.33 – Cases of Aviation Cyberattack

How does it work?

Cybercrime – tactics, techniques, and procedures:

- Malware injection;
- Phishing campaigns;
- Social engineering;
- Mobile malware;
- Physical theft of hardware.

Malware Infection Techniques

- Phishing – widespread email – lots of victims;
- Spear-phishing – targeted email aimed at a few victims;
- Drive by download – tricking search engines (Google, Bing, Yahoo, etc.) to display links to malicious content;
- Fake Anti-virus software – alarming user with false infection warning, tricked into downloading software;
- Pharming/DNS Re-direction – modifying user PC or DNS provider to send traffic to malicious servers;
- Drive-by email – opening email or preview panel.

Mobile malware

- Malware infections of mobile smartphones increased by more than 780% from 2011 to the end of 2012
- 99% of the mobile malware available specifically targeted Android devices
- Over 6,000 new pieces of Android malware per month in the latter half of 2012
- The largest category of mobile malware in 2012 was SMS Trojans masquerading as legitimate apps. All were designed to target bank accounts

Where cybercriminals come from…

- Nation-State Actors – Highly Sophisticated – *state and corporate secrets;*
- Criminal Rings – Organized crime focused on cyber – *money-driven;*

- Hacktivists – Cybercriminals with a 'cause' – *political causes*;
- Script Kiddies – Up and comers – *making a name for themselves*.

Location and Risk

- Hand-Held Devices;
- Laptops;
- Desktops;
- Servers/Databases;
- Web Applications;
- POS Equipment;
- Thumb Drives;
- The Cloud – SaaS.

Back to the Basics

- Poor handling of usernames and passwords
- Clicking on links from disguised sources
- Mobile malware
- Downloading suspicious software

Cybersecurity is a people problem, not a technology problem.

How to counteract?

"Cybersecurity has become a cost of doing business for airports. All airports can afford it; it is a matter of how much and what sacrifices they are willing to make."

The Usual Suspects

- Desktops;
- Servers;
- Network devices;

Threat Landscape:

Airports

- Flight Information Systems (FIDS);
- Airfield lighting controls;
- Heating and ventilation systems;
- Baggage handling systems;
- Access control devices;
- Other mission-critical systems that rely on digital technology.

Interconnectivity

- Airlines;
- Concessionaires;
- Tenants;
- Vendors;
- Passengers;
- Anyone who is connected to the airport's network.

Essential Practices

- Identify vulnerabilities and prioritize based on the potential impact of a successful attack;
- Adopt countermeasures;
- Hire/Assign a CISO:
    - Incident response team;
    - Threat assessments;
- Audit human and computer behaviour.

8.6 Big Data

Since the advent of mankind, knowledge has been limited by several factors: (i) the accurate observation of facts; (ii) the rational identification of their causes; (iii) the definition of effective strategies; (iv) their implementation in the right time frame. Modern technology has advanced most of these fields: (i) a variety of sensors improve situational awareness; (ii) merging sensor data minimizes errors of interpretation; (iii) decision aids and simulations improve predictive capabilities; (iv) computing and automation implement processes at a rate beyond human capabilities. All these activities give increased access to data, compound the problem of digesting it and increase the benefits of successfully doing so. Modern telecommunications, data storage and computing can process the large amounts of data gathered to put it to good use. A fast-growing field is to use onboard monitoring of aircraft systems for preventive and on-condition maintenance avoiding long and costly interruptions of service; another is to use operational data to guide design choices for higher reliability and lower cost. At the next level, individual aircraft operations can be monitored to improve fleet-level efficiency at the scale ranging from an airline to the air traffic management (ATM).

Some of the multiple uses of big data are considered in more detail next (Key Topic T8.5). The processing of big data may use cognitive (Key Topic T8.6) and quantum computing (Key Topic T8.7) and artificial intelligence (section 8.7).

KEY TOPIC T8.5 BIG DATA

With the digitization of most of the processes, the emergence of different social network platforms, blogs, deployment of different kind of sensors, adoption of hand-held digital devices, wearable devices and explosion in the usage of the Internet, huge amounts of data are being generated continuously. Applications as the Internet has changed the way businesses operate, functioning of several sectors and lifestyle of people around the world. Today, this trend is in a transformative stage, where the rate of data generation is very high, and the type of data being generated surpasses the capability of existing data storage techniques. These data carry a lot more information than ever before due to the emergence and adoption of the Internet.

Over the past two decades, there has been tremendous growth in data. This trend can be observed in almost every field. According to a report by International Data Corporation (IDC), a research company claims that between 2012 and 2020, the amount of information in the digital universe will grow by 35 trillion gigabytes.

In the mid-2000s, the emergence of social media, cloud computing, and processing power (through multi-core processors and GPUs) contributed to the rise of big data. As an example, in December 2015, Facebook had an average of 1.04 billion daily active users, 934 million mobile daily active users, available in 70 languages, 125 billion friend connections, 205 billion photos uploaded every day 30 billion pieces of content, 2.7 billion likes, and comments are being posted and 130 average number of friends per Facebook user.

Understanding the great amount of data can help organisations to make informed decisions and provide a competitive advantage. In past years, organisations used simple data analysis techniques that helped them to plan and take decisions. However, due to the increase in the size of data especially the unstructured form of data, it has become almost impossible to process these data with the existing storage techniques.

Storage and retrieval of a vast amount of structured as well as unstructured data at a desirable time lag is a challenge. Some of these limitations to handle and process a vast amount of data with the traditional storage techniques led to the emergence of the term Big Data. Big Data is about how these data can be stored, processed, and comprehended such that it can be used for predicting the future course of action with great precision and acceptable time delay.

The current and emerging focus of big data analytics is to explore traditional techniques such as rule-based systems, pattern mining, decision trees and other data mining techniques to develop business rules even on the large data sets efficiently. It can be achieved by either developing algorithms that use distributed data storage, in-memory computation or by using cluster computing for parallel computation. Earlier these processes were carried out using grid computing, which was overtaken by cloud computing in recent days.

- Grid computing: it is a means of allocating the computing power in a distributed manner to solve problems that are typically vast and requires lots of computational time and power. It works on the principle of voluntary basis, where the users share their computing and memory resources to be used by others. In this setting, the goal is to access computers only when needed and to scale the problems in such a manner that even small computers can contribute to the grid. Every computer that is connected to the Internet and wants to become a part of the grid is considered a node in an extremely large computing machine. The main advantage of this computing technique is that it offers an opportunity to harness unused computing power. There are several applications which are using this technology such as weather, astronomy, medicine, multi-player gaming, etc. However, this technology has several disadvantages such as financial, social, legal and regulatory issues.
- Cloud computing: It has its roots from grid computing and other related areas like utility computing, cluster computing and distributing systems, in general. Cloud computing refers to the concept of computing at a remote location with control at the users end through a thin client system, computer or even mobile phones. Processing, memory, and storage will be done at the service providers' infrastructure. Users need to connect to the virtual system residing at some remote location, which might run several virtual operating systems on physical servers with the help of virtualisation. It supports all sorts of fault-tolerant features like live migration, scalable storage, and load balancing. Cloud computing also suffers from similar drawbacks of grid computing like data location, data replication, data segregation, security threats, regulatory compliances, recovery issues, long-term viability, high dependency on the Internet for accessing the remote virtual machine, different laws of different countries, investigative support, etc.

In the following image (Figure 8.34), it can be seen a map of the future of big data technologies with an array of emerging technologies that are reaching new levels of diversity, resilience, and adoption:

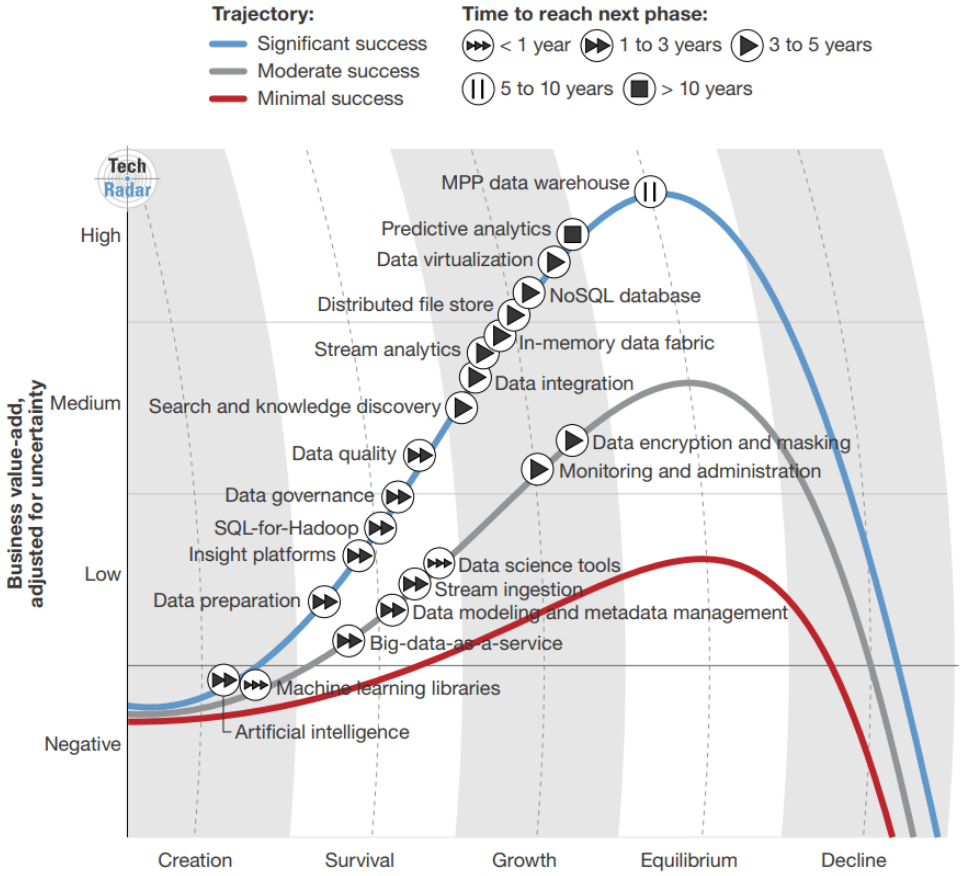


Figure 8.34 - Big data technologies

Source 1: TechRadar™: Big Data, Q1 2016

T8.5.1 Definition and Dimensions

The term big data has been defined in different ways, but there is not a specific definition. For example, in 2010, Apache Hadoop defined big data as "datasets, which could not be captured, managed, and processed by general computers within an acceptable scope". Following this, in 2011, McKinsey Global Institute defined big data as "datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyse". In addition, International Data Corporation (IDC) defines "big data technologies as a new generation of technologies and architectures, designed to economically extract value from very large volumes of a wide variety of data, by enabling high-velocity capture, discovery, and/or analysis".

On the other hand, Academicians define big data as a huge size of unstructured data produced by a high-performance heterogeneous group of applications that spans from social network to scientific computing applications. The datasets range from a few hundred gigabytes to zettabytes that it is beyond the capacity of existing data management tools to capture, store, manage and analyse.

However, in addition to defining big data, there is a need to understand how to make the best use of this data to obtain valuable information for decision making.

Initially, big data was characterized by the following dimensions, which were, often, referred to as 3V model:

- Volume: it refers to the magnitude of the data that is being generated and collected. The data volume is growing ever faster and, in the future, as the storage capabilities increase, it will be possible to store and capture data more efficiently.

- Velocity: velocity refers to the rate of generation of data. Traditional data analytics is based on periodic updates (daily, weekly, or monthly). With the increasing rate of data generation, big data should be processed and analysed in real or near real-time to make informed decisions. The time role is a critical factor.
- Variety: Variety refers to different types of data that are being generated and captured. They are within the category of unstructured data, which cannot be organised using a pre-defined data model, unlike the structured data. Examples include video, text, and audio.

Later, one more dimension has been added:

- Veracity: Coined by IBM, veracity refers to the unreliability associated with the data sources. There is a need to differentiate reliable data from uncertain and imprecise data and manage the uncertainty associated with the data.

T8.5.2 Sources of Big Data

The data can be captured from different sectors such as astronomy, agriculture, industry, etc. In addition, the Internet of Things (IoT) has become one of the main sources of data. The following Table 8.3 summarises the various types of data produced in different sectors:

Sector	Data produced	Use
Astronomy	Movements of stars, satellites, etc.	To monitor the activities of asteroid bodies and satellites.
Financial	News content via video, audio, twitter and news report	To make trading decisions
Healthcare	Electronic medical records and images	To aid in short-term public health monitoring and long-term epidemiological research programs
Internet of Things (IoT)	Sensor data	To monitor various activities in smart cities
Life sciences	Gene sequences	To analyse genetic variations and potential treatment effectiveness
Media/Entertainment	Content and user viewing behaviour	To capture more viewers
Social Media	Blog posts, tweets, social networking sites, log details	To analyse the customer behaviour pattern
Telecommunications	Call Detail Records (CDR)	Customer churn management
Transportation, Logistics, Retail, Utilities	Sensor data generated from fleet transceivers, tag readers and smart meters	To optimise operations
Video surveillance	Recordings from CCTV to IPTV cameras and recording system	To analyse behavioural patterns for service enhancement and security

Table 8.3 - Sources of data

Source: Big Data: Challenges, Opportunities and Realities, Bhadani and Jothimani, 2016

T8.5.3 Big Data Value Chain

Value Chain, the concept introduced by Porter (1980), refers to a set of activities performed by a firm to add value at each step of delivering a product/service to its customers. Similarly, the data value chain refers to the framework that deals with a set of activities to create value from available data. It can be divided into seven phases: data generation, data collection, data transmission, data pre-processing, data storage, data analysis and decision making.

- Data generation: The first step of the big data value chain is the generation of data. Normally, data is generated from various sources that include data from blogs, tweets, etc.
- Data Collection: in this phase, the data is obtained from all possible data sources. The most commonly used methods are log files, sensors, web crawlers and network monitoring software.
- Data Transmission: Once the data is collected, it is transferred to a data storage and processing infrastructure for further processing and analysis.
- Data Pre-processing: The data collected from various data sources may be redundant or inconsistent. For that reason, in this phase, the data is pre-processed to improve the data quality required for analysis. This also helps to improve the accuracy of the analysis and reduce the storage expenses.
- Data Storage: The big data storage systems should provide reliable storage space and powerful access to the data.
- Data Analysis: Once the data is collected, transformed and stored, the next process is data exploitation or data analysis, by defining a set of metrics for a particular problem taking as a base the collected and transformed data as well as selecting the suitable architecture and the appropriate algorithms.
- Decision Making: Based on the analysis of the data collected and results obtained, the next step is to make informed decisions and plan for necessary actions.

T8.5.4 Technologies for Analysing Big Data

Tools that are being used to collect data encompass various digital devices (for example, mobile devices, camera, wearable devices, and smartwatches) and applications that generate enormous data in the form of logs, text, voice, images, and video. In order to process these data, several researchers are coming up with new techniques that help better representation of the unstructured data, which makes sense in big data context to gain useful insights that may not have been envisioned earlier.

- Not only Structured Query Languages (NoSQL): It is the most commonly used database query language. The data is stored in a data warehouse using a dimensional approach and normalized approach. NoSQL stores and manages unstructured data and it allows the scalability of data. Few examples of NoSQL databases are HBase, MongoDB, and Dynamo.
- Hadoop: In 2005, an open-source Apache Hadoop project was conceived and implemented based on Google File System and Map Reduce programming paradigm. Apache Hadoop is a software framework that supports distributed applications under a free license. It allows applications to work with thousands of nodes and great amounts of data.
    - Hadoop Distributed File System (HDFS): HDFS is the fault-tolerant, scalable, highly configurable distributed storage system for a Hadoop cluster. Data in the Hadoop cluster is broken down into pieces by HDFS and are distributed across different servers in the Hadoop cluster. A small chunk of the whole data set is stored on the server.
    - Hadoop MapReduce: It is a software framework for distributed processing of vast amounts of data in a reliable, fault-tolerant manner. It is divided into two phases: The Map phase, in which the workload is divided into smaller sub-workloads, which are assigned to the Mapper, and it processes each unit block of data to produce a sorted list of pares. Then, in the Reduce phase, the previous list is analysed and merged to produce the final output which is written to the HDFS in the cluster.

The following Table 8.4 summarizes the big data capabilities and the available main technologies:

Big data capability	Primary Technology	Features
Storage and management capability	Hadoop Distributed File System (HDFS)	Open-source distributed file system, Runs on high-performance commodity hardware, Highly scalable storage and automatic data replication

Big data capability	Primary Technology	Features
Database capability	Oracle NoSQL	Dynamic and flexible schema design, Highly scalable multi-node, multiple data centre, fault-tolerant, ACID operations, High-performance key-value pair database
	Apache HBase	Automatic failover support between Region servers, Automatic and configurable sharing of tables
	Apache Cassandra	Fault tolerance capability for every node, Column indexes with the performance of log-structured updates and built-in caching
	Apache Hive	Query execution via MapReduce, Uses SQL-like language HiveQL, Easy ETL process either from HDFS or Apache HBase
Processing capability	MapReduce	Distribution of data workloads across thousands of nodes, Breaks problem into smaller sub-problems
	Apache Hadoop	Highly customizable infrastructure, Highly scalable parallel batch processing, Fault-tolerant
Data integration capability	Oracle big data connectors, Oracle data integrator	Exports MapReduce results to RDBMS, Hadoop, and other targets, Includes a Graphical User Interface
Statistical analysis capability	R and Oracle R Enterprise	Programming language for statistical analysis

Table 8.4 - Big data capabilities and main technologies

Source 2: Big Data: Challenges, Opportunities and Realities, Bhadani and Jothimani, 2016

T8.5.5 Software Tools

Several tools allow processing and analysing data. Many new languages, frameworks and data storage technologies have emerged that supports the handling of big data:

- R: is an open-source statistical computing language that provides a wide variety of statistical and graphical techniques to derive insights from the data. It has effective data handling and storage facility and supports vector operations with a suite of operators for faster processing. A huge number of packages supports R and it is available on Windows, Linux, and Mac platforms. It is good to support reading and writing in a distributed environment, which makes it appropriate for handling big data, but its main challenges are memory management, speed, and efficiency.
- Python: is yet another popular programming language, which is open source and is supported by Windows, Linux, and Mac platforms. Libraries such as NumPy, Scikit, and Pandas support some of the popular packages for machine learning and data mining for data pre-processing computing and modelling. Python is very user-friendly and great for quick analysis of a problem.
- Scala: is an object-oriented language and it is becoming a popular programming tool for handling big data problems. It requires java virtual machine environment.
- Apache Spark: is an in-memory cluster computing technology designed for fast computation, which is implemented in Scala. It uses Hadoop for storage purpose as it has its own cluster management capability. It supports R, Map Reduce, SQL, data streaming, graph processing algorithms and machine learning algorithms.
- Apache Hive: is an open-source platform that provides facilities for querying and managing large datasets residing in distributed storage. It is similar to SQL and it uses Map Reduce for processing the queries and supports developers to plug in their custom mapper and reducer codes.
- Apache Pig: is a platform that allows analysts to analysing large data sets. It is a high-level programming language, called as Pig Latin for creating MapReduce programs, that requires Hadoop for data storage. The Pig

Latin code is extended with the help of User-Defined Functions that can be written in Java, Python, and a few other languages.

- Amazon Elastic Compute Cloud (EC2): is a web service that provides compute capacity over the cloud. It gives full control of the computing resources and allows developers to run their computation in the desired computing environment. It is one of the most successful cloud computing platforms.

T8.5.5 Applications of Big Data

Big data have great applications in several sectors, which are described below:

Healthcare:

Data analysts obtain and analyse information from multiple sources to gain insights. The multiple sources can be various: electronic patient record, clinical decision support system including medical imaging, physician's written notes and prescription, pharmacy, and laboratories, etc. The integration of clinical, public health and behavioural data helps to develop a robust treatment system, which can reduce the cost and at the same time, improve the quality of treatment. Data obtained from sensors are monitored and analysed for adverse event prediction and safety monitoring.

In addition, obtaining information from external sources such as social media helps in the early detection of epidemics and precautionary efforts. For example, after the earthquake in Haiti in January 2010, analysis of tweets helped to track the spread of Cholera in the region.

Telecommunication

Through data analysis such as demographic data (gender, age, marital status, and language preferences), customer preferences, household structure and usage details, it can be possible to improve the quality of service and customers experience, modelling their preferences and offering a relevant personalized service to them. This is known as targeted marketing, which improves the adoption of mobile services and reduces churn. Companies' analyses data to identify the call patterns to offer different plans to customers. The services are marketed to the customers through a call or text message and their responses are recorded for further analysis.

In addition, telecom companies are working towards combating telecom frauds since traditional fraud management systems are not efficient in detecting new types of fraud. In order to overcome the limitations of the traditional fraud management system, real-time data are being analysed to minimize the losses due to fraud. For example, Mobileum Inc., one of the leading telecom analytics solution providers, is working towards providing a real-time fraud detection system using predictive analytics and machine learning.

Financial Firms

Currently, capital firms are using advanced technology to store huge volumes of data. However, increasing data sources like the Internet and Social media require them to adopt big data storage systems in addition to the need for real-time processing of data. Capital markets are using big data in preparation for regulations, anti-money laundering, fraud mitigation, pre-trade decision-support analytics including sentiment analysis, predictive analytics, and data tagging to identify trades.

Retail

Evolution of e-commerce, online purchasing, social-network conversations and recently location-specific smartphone interactions contribute to the volume and the quality of data for data-driven customization in retailing. By observing behaviour and purchasing patterns of customers, nowadays, e-commerce firms use this data analysis to segment and target the customers as well as to track the flow of clients and recommend products in real-time.

In addition, analytics help the retail companies to manage their inventory. For example, Stage stores, one of the brand names of Stage Stores Inc., which operates in more 40 American states, used to analytics to forecast the order for different sizes of garments for different geographical regions.

Marketing

Marketing analytics helps the organizations to evaluate their marketing performance, to analyse the consumer behaviour and their purchasing patterns, to analyse the marketing trends which would aid in modifying the marketing strategies like the positioning of advertisements in a webpage, implementation of dynamic pricing and offering personalized products.

New Product Development

Analysing data sources, both internal and external can allow understanding the customers' requirement for a new product, gathering ideas for a new product as well as understanding the added feature included in a competitor's product. Proper analysis and planning during the development stage can minimize the risk associated with the product, increase the customer lifetime value and promote brand engagement. For example, Ribbon UI in Microsoft 2007 was created by analysing the customer data from previous releases of the product to identify the commonly used features and making intelligent decisions.

Banking

The investment worthiness of the customers can be analysed using demographic details, behavioural data, and financial employment. The concept of cross-selling can be used here to target specific customer segments based on past buying behaviour, demographic details, sentiment analysis, etc.

Energy and Utilities

Consumption of water, gas and electricity can be measured using smart meters at regular intervals of one hour. During this interval, a huge amount of data is generated and analysed to change the patterns of power usage. The real-time analysis reveals energy consumption pattern, instances of electricity thefts and price fluctuations.

Insurance

Personalized insurance plan is adapted for each customer using updated profiles of changes in wealth, customer risk, home asset value, and other data inputs. Recently, the insurance companies collect driving data of customers such as miles driven, routes driven and time of day, by using sensors in their cars. Comparing individual driving pattern and driver risk with the statistical information available such as peak hours of drivers on the road develops a personalized insurance plan. This analysis of driver risk and policy gives a competitive advantage to the insurance companies.

Education

With the advent of computerized course modules, it is possible to assess academic performance in real-time. This helps to monitor the performance of the students after each module and give immediate feedback on their learning pattern. It also helps the teachers to assess their teaching pedagogy and modify based on the students' performance and needs. Behavioural patterns such as students that require special attention or those students who can face challenging tasks can be predicted.

As an example, the following image (Figure 8.35) shows the main sectors, which have been described previously, in which big data have applications:

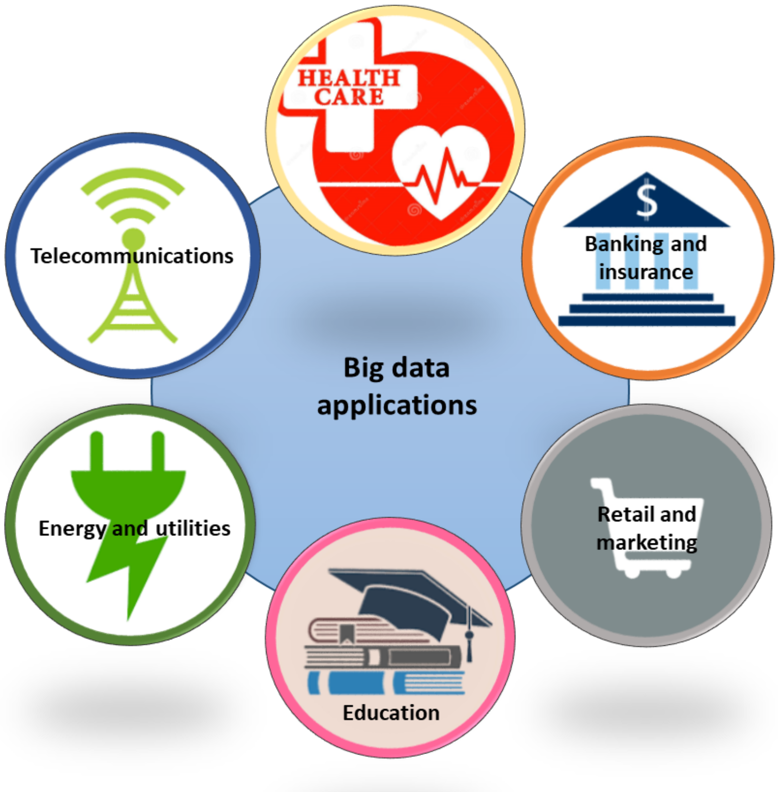


Figure 8.35 - Big data applications

Apart from the sectors mentioned previously, big data analytics has a great number of applications that can be used in many other sectors, such as aviation, construction, meteorology, and material sciences.

T8.5.6 Applications of Big Data in Aviation

The new generation of aircraft generates a lot of data from multiple sources (Figure 8.36): flight tracking data, passenger information, airport operations, aircraft information, weather data, airline information, market information and air safety reports besides heath and usage monitoring systems (HUMS) of engines and other components. In the following image, it can be seen examples of data sources form the aviation industry:

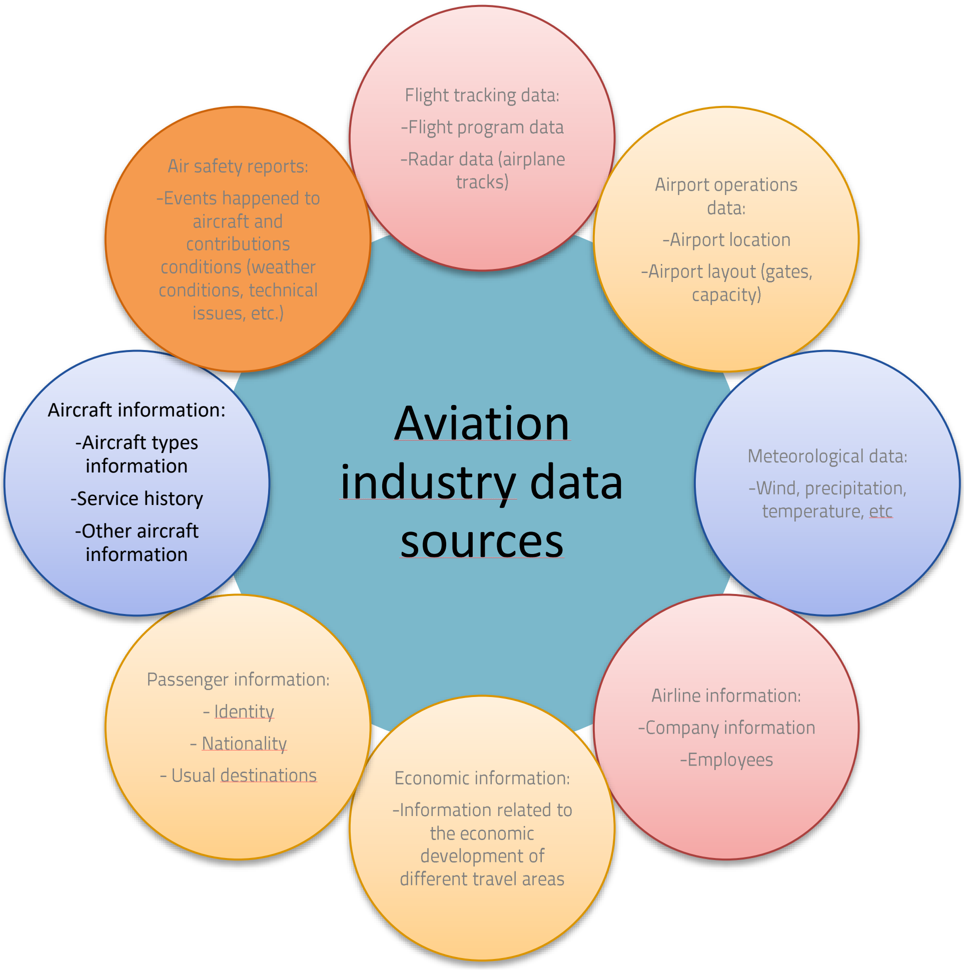


Figure 8.36 - Aviation industry data sources

Some of these data can be obtained through thousands of sensors and sophisticated digitalised systems that are installed onboard an aircraft. The newest generation of jets can collect, with each flight, more than 30 times the amount of data the previous generation of wide-bodied jets produced. Although currently only about one-tenth of the global fleet is made up of these technologically advanced aircraft, it is expected that in a decade this number will increase to the double. By 2026 (Figure 8.37), annual data generation should reach 98 billion gigabytes, or 98 million terabytes, according to a 2016 estimate by Oliver Wyman. By then, the newest generation aircraft will be spewing out between five and eight terabytes per flight, up to 80 times what older planes today generate.

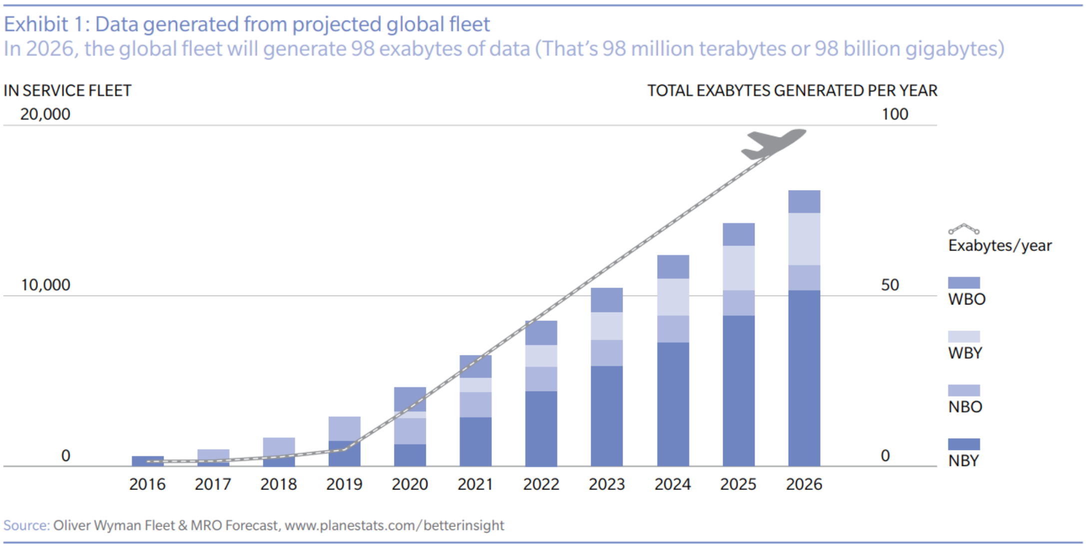


Figure 8.37 - Data generated form aircraft fleet

Source 3: Oliver Wyman, MRO Survey 2016

Due to this great amount of data, IA and big data analytics will be essential in the future in order to process all this data and extract useful information in real-time, since this capacity is very limited nowadays. With hundreds of planes, thousands of flights, and millions of employees and passengers, there is now too much data and too many variables for humans to sort through fast enough to fix problems or even prioritise potential threats. While much of this activity today is mostly reactive, the next step will be for aviation to proactively avoid some of the delays, congestion, and inefficiencies that annoy passengers and keep the global industry at single-digit profit margins.

Using big data analytics to process efficiently the great amount of data from different sources can have several applications on aviation:

Optimising operations

With all the data provided by the newest aircraft, it could be possible to optimise fuel consumption, crew deployment and flight operations. In addition, maintenance could be improved by anticipating parts that need to be replaced, air congestion could be reduced, flight routes could be altered in advance of take-off in order to avoid adverse weather conditions and passengers could be kept informed about schedules and options from the minute they leave their home for the airport. These improvements would make aircraft easier to maintain and more efficient. It also may reduce crew fatigue with more precise scheduling and fill in gaps from anticipated pilot shortages. Moreover, the data could help with the next generation of aircraft by providing information about new ways to improve systems design and performance.

Cost

The new connectivity and advanced analytics also mean savings for airlines; Oliver Wyman's estimate is between 2 percent and 2.5 percent of total global operating costs, which translates to something between $5 billion and $6 billion annually. However, it may take several years, even a decade, to achieve these possibilities. In addition, it could be possible to improve overall fuel cost (not just the consumption) considering energy prices, when/where to refuel, optimal flight and taxi paths as well as when/how much to hedge for the fuel

Maintenance

For aviation companies, delays and cancellations are a huge and expensive problem. Up to 30% of the total delay time is due to unplanned maintenance. Advanced analytics rationalize, predict and streamline maintenance, helping aviation clients increase maintenance efficiency, improve the health of their fleet, and reduce delays and cancellations. This predictive maintenance approach can also help improve areas like supply chain optimization, inventory allocation and planning, aircraft reliability improvement and operation and schedule planning.

Therefore, the benefits are:

- Reduced maintenance cost and improved aircraft availability through optimization of the maintenance program.
- Reduced maintenance turnaround time through efficient troubleshooting.
- Reduced parts inventory requirements through integrated supply chain and planning

Weather forecasting

All the data provided by aircraft can be used to predict adverse weather events before they occur. This can have significant impact as flight plans are quite sensitive to weather and knowing in advance future weather events can lead to fewer flight diversions, cancelled flights, and costly delays besides reducing risks.

Safety

It is expected that global air traffic increases in the next 10-15 years and, for that reason, the number of accidents will correspondingly increase if nothing is done to improve it. Therefore, new and efficient ways of improving air safety need to be explored. Accident reduction or safety increase have been decreasing total accidents in spite of more flights.

Due to the vast amount of data produced and collected every day in aviation, valuable information cannot be discovered with traditional analysis method. For example, the reports developed once an accident or incident has happened are an example of the data collected, including information such as aircraft descriptions, pilots age, pilot experience, operators, time of day, weather, and the factors contributing to the accident (or incident). These reports include both structured and narrative fields. The structured data can be analysed easily using queries from databases and running their results through graphic tools. Among narrative data, the situation is totally different. There were no tools to analyse textual data until data mining tools have been developed. Data mining is a broad field of data science, which has had a great development in recent years. Data mining was developed to make predictions on future data based on patterns found in the collected data.

Data mining could be used to improve aviation safety by analysing all the data collected from the reports and searching for patterns and anomalies that indicate potential incidents and hazardous situations before they happen. However, this method presents several limitations. For example, the task requires some knowledge of what should be searched for and found and, therefore, it is necessary to find a method to determine the relevant and important data. In addition, as the data included in reports is overly generalised, it is difficult to identify unknown patterns, and, in consequence, data mining usually confirms known trends.

KEY TOPIC T8.6 COGNITIVE COMPUTING

The machines of tomorrow, cognitive systems, will forever change the way people interact with computing systems to help people extend their expertise across any domain of knowledge and make complex decisions involving extraordinary volumes of fast-moving Big Data.

The cognitive systems are a category of technologies that uses natural language processing and machine learning to enable people and machines to interact more naturally to extend and magnify human expertise and cognition. These systems will learn and interact to provide expert assistance to scientists, engineers, lawyers, and other professionals in a fraction of the time it now takes. Far from replacing our thinking, cognitive systems will extend our cognition and free us to think more creatively. In so doing, they will speed innovations and ultimately help build a Smarter Planet.

Cognitive computing refers to systems that learn at scale, reason with purpose, and interact with humans naturally. Rather than being explicitly programmed, they learn and reason from their interactions with us and from their experiences with their environment. They are made possible by advances in several scientific fields over the past half-century and are different in important ways from the information systems that preceded them.

The success of cognitive computing will not be measured by Turing tests or a computer's ability to mimic humans. The Turing test, developed by Alan Turing in 1950, is a test of a machine's ability to exhibit intelligent behaviour equivalent to, or indistinguishable from, that of a human.

It will be measured in more practical ways, like return on investment, new market opportunities, diseases cured, and lives saved.

T8.6.1 The History of Computing and the Rise of Cognitive Features

To understand the future of cognitive computing, it is important to place it in historical context (Figure 8.38).

a. **The Tabulating Era (1900s - 1940s)**. The birth of computing consisted of single-purpose mechanical systems that counted, using punched cards to input and store data, and to eventually instruct the machine what to do (albeit in a primitive way). These tabulation machines were essentially calculators that supported the scaling of both business and society, helping us to organize, understand, and manage everything from population growth to the advancement of a global economy.

b. **The Programming Era (1950s - present)**. The shift from mechanical tabulators to electronic systems began during World War II, driven by military and scientific needs. Following the war, digital "computers" evolved rapidly and moved into businesses and governments. They performed if/then logical operations and loops, with instructions coded in software. Originally built around vacuum tubes, they were given a huge boost by the invention of the transistor and the microprocessor, which came to demonstrate "Moore's Law," doubling in capacity and speed every 18 months for six decades. Everything we now know as a computing device — from the mainframe to the personal computer, to the smartphone and tablet — is a programmable computer.

c. **The Cognitive Era (2011 -).** The potential for something beyond programmable systems was foreseen as far back as 1960 when computing pioneer J.C.R. Licklider wrote his seminal paper "Man-Computer Symbiosis." Much of modern computing is based on Licklider's research and insights:

"Man-computer symbiosis" is an expected development in cooperative interaction between men and electronic computers. It will involve very close coupling between the human and the electronic members of the partnership. The main aims are: to let computers facilitate formulate thinking as they now facilitate the solution of formulated problems, and to enable men and computers to cooperate in making decisions and controlling complex situations without inflexible dependence on predetermined programs...

Preliminary analyses indicate that the symbiotic partnership will perform intellectual operations much more effectively than man alone can perform them." - J.C.R. Licklider, "Man-Computer Symbiosis," March 1960 Licklider knew that cognitive computing would be a necessary and natural evolution of programmable computing, even if he didn't yet know how it would be accomplished. Fifty years later, massively parallel computing and the accumulation of oceans of structured and unstructured data would lay the groundwork for cognitive computing.

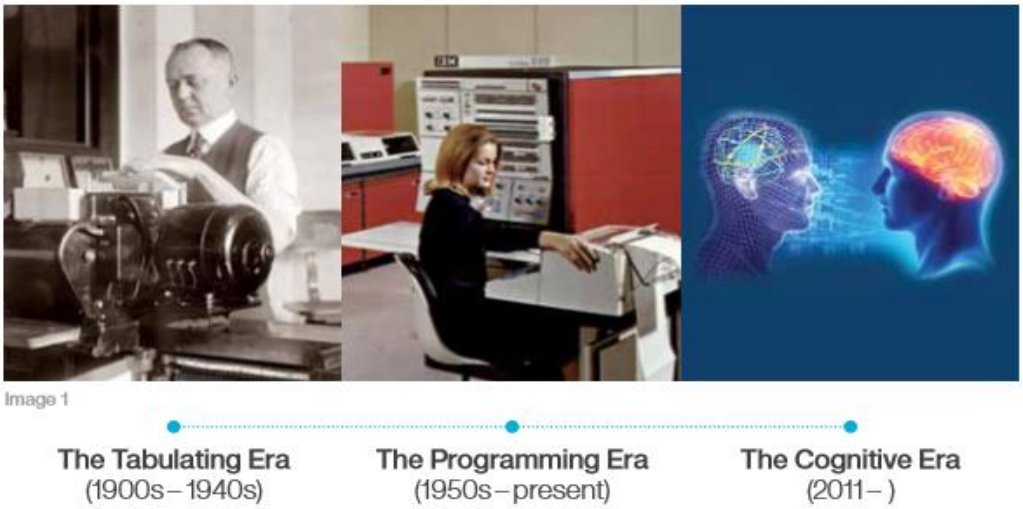


Figure 8.38 - Computing's evolution

Source 4: IBM Computing cognition and the future of knowing, Dr John E. Kelly III

T8.6.2 Watson

In February 2011, the world was introduced to Watson, IBM's cognitive computing system. It was the first widely seen demonstration of cognitive computing. Watson's ability to answer subtle, complex, pun-laden questions made clear that a new era of computing was at hand. Watson has tackled increasingly complex data sets and developed understanding, reasoning, and learning that go far beyond deciphering (Figure 8.39). Indeed, the goal of cognitive computing is to illuminate aspects of our world that were previously invisible, patterns and insight in unstructured data, in particular, allowing us to make more informed decisions about more consequential matters.

The true potential of the Cognitive Era will be realized by combining the data analytics and statistical reasoning of machines with uniquely human qualities, such as **self-directed goals**, **common sense,** and **ethical values**. This is what Watson was built to do and is in fact already doing.

T8.6.3 Applications of Cognitive Computing

- Economic area: Banks are analysing customer requests and financial data to surface insights to help them make investment recommendations. Companies in heavily regulated industries are querying the system to keep up with ever-changing legislation and standards of compliance.
  In a global economy and society where value increasingly comes from information, knowledge and services, this data represents the most abundant, valuable and complex raw material in the world. And until now, we have not had the means to mine it effectively.
- Health area: oncologists are testing ways in which cognitive systems can help interpret cancer patients' clinical information and identify individualized, evidence-based treatment options that leverage specialists' experience and research. Computer science is going to evolve rapidly, and medicine will evolve with it. This is co-evolution.
- Aeronautical area: there are many applications in the field of aeronautics (Figure 8.40), of which the following stand out:
  1. Turbulence detection. Turbulence, especially that caused by thunderstorms (convectively induced turbulence) has been hard to detect by traditional meteorological sensing methods. With **IBM Watson**, carriers are developing an intelligent detection system that combines IoT (Internet of Things) sensor data, billions of data points from The Weather Company and real-time updates from nearby pilots.
  2. Aviation Maintenance. The company IBM has taken Maximo's 30 years of maintenance/EAM experience and has combined it with IBM's 50+ years of aerospace experience (Apollo, Space Shuttle, & Sabre) and

created **Maximo for Aviation**. It addresses the need for a highly configurable, easily upgradeable, web-built enterprise application for aviation maintenance.

3. Help the pilot to develop a problem with a hydraulic system in flight. The pilot can simply describe the situation in spoken, natural human language. Watson can interpret the problem logically and then review the technical materials relevant to a solution. It could then make a series of recommendations to the pilot.
4. Reduce delays at airports. Using advanced content analytics, Watson can examine a plane's maintenance history and recommend probable causes and solutions to maintenance issues. How and where would it be integrated into flight control systems?
5. Communicate with the customers on travel and add-on travel services such as; a hotel, rental car, and even restaurant suggestions. One key area where Watson can help airlines is through real-time personalization and offers. Watson can provide real-time personalization of price and offers by estimating a customer's propensity-to-pay and response to offers. To do this, Watson learns about the customer, their journey, and the various product attributes.
6. A new technology dubbed **R3** designed to better predict and manage air traffic volume as well as deliver more real-time information about an aviation event. R3 stands for responsive, reliable and real-time and created at IBM's Watson research lab. The joint project was designed to coordinate more flights in the same airspace. The air traffic issue is a big one considering that flight traffic is expected to double or triple by 2025.
7. This picture shows how Watson IoT platform and **Weather Company** data can be used to integrate sensors and mobile clients. With advances in avionics and the availability of cheap computing resources such as Raspberry Pi, a simple ground station may be easily built. Once configured, ground stations can be replicated using Docker to be able to cover large areas.

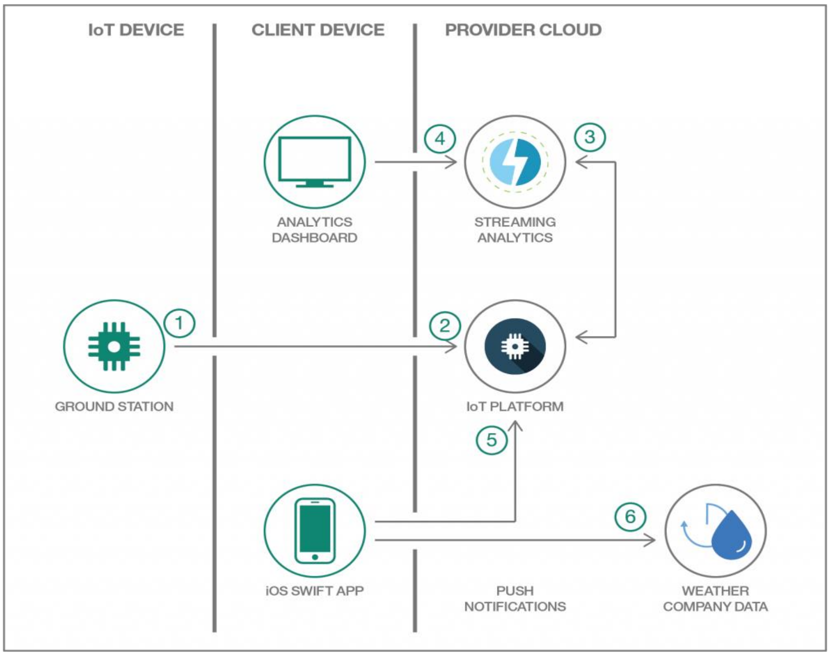


Figure 8.39 - Watson IoT platform and Weather Company data

Source 5: IBM DeveloperWorks

8. One of the major goals of researchers at NASA's Jet Propulsion Laboratory (JPL) is to remotely control vehicles for extra-planetary exploration, rather than manually manoeuvring vehicles or programming robotic sequences in advance and letting them run.
9. Another application of cutting-edge Virtual Reality (VR) tech in space exploration currently in use is testing new vehicles in virtual space before building prototypes in physical space (Figure 8.41).

Additionally, VR helps the crews prepare for obstacles they may encounter on missions. This is especially useful in orbital trajectory planning where pilots can practice manoeuvring certain flight paths according to the actual physics of space but from the safety of a space-like digital environment. VR training is also handy to help prep for day-to-day life in space.

10. Researchers at NASA's Armstrong Flight Research Centre have started exploring the possibility of employing IBM Watson as a flight operations advisor. In this role, NASA flight crews would leverage Watson's ability to crunch large amounts of aviation data that come in from any number of devices to help with rapid decision-making. By tasking Watson with the heavy research needed to quickly identify and respond to unforeseen circumstances in-flight, NASA hopes to offload the brunt of real-time research usually performed by both in-flight and ground crews on the cognitive computer. In a not-too-distant future, cloud-based cognitive computer like Watson could just as easily be our new co-pilots.

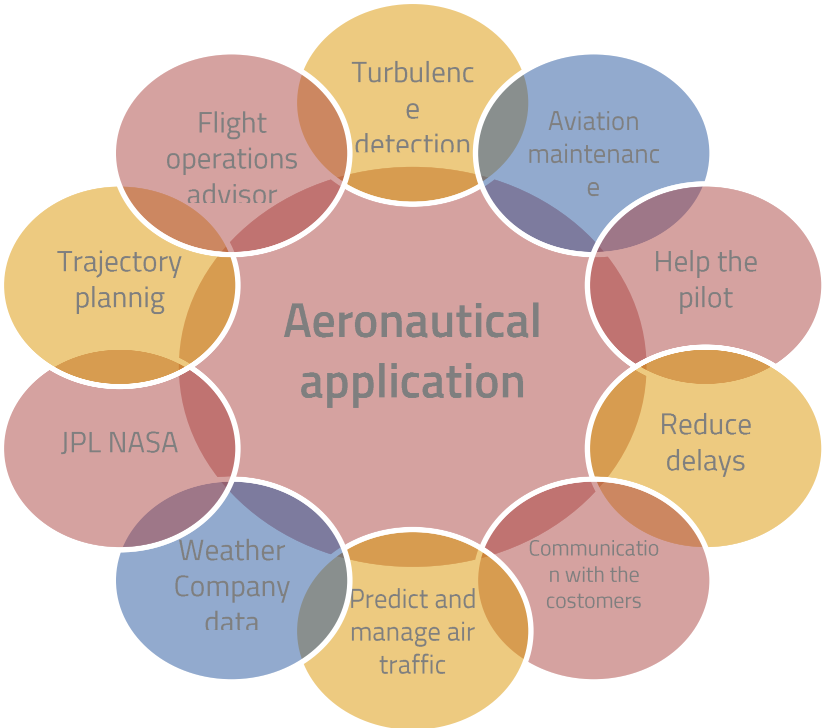


Figure 8.40 - Aeronautical applications of cognitive computing

Figure 8.41 - NASA Virtual reality and cognitive computing, Wired Brand Lab

Source 6: IBM Internet of Things blog

Some very complex problems like Air Traffic Management (ATM) still defy computing tools. IBM famously failed in the 1980s a large contract of 6.3 B$ from FAA (Federal Aviation Administration) to automate ATM in the US; this was before the advances in cognitive computing that are now contributing to model parts of the ATM system.

KEY TOPIC T8.7 QUANTUM COMPUTING

Quantum computers are incredibly powerful machines that take a new approach to processing information. Built on the principles of quantum mechanics, they exploit complex and fascinating laws of nature that are always there but usually remain hidden from view. By harnessing such natural behaviour, quantum computing can run new types of algorithms to process information more holistically. This extraordinary scaling will advance the state of the art in software verification and validation, cryptography, drug discovery, machine learning, cybersecurity, finance, and many other areas where innovation is bounded by the limits of high-performance computing.

In quantum computing, a **qubit** (short for "quantum bit") is a unit of quantum information, the quantum analogue to a classical bit. Qubits have special properties that help them solve complex problems much faster than classical bits. One of these properties is superposition, which states that instead of holding one binary value ("0" or "1") like a classical bit, a qubit can hold a combination of "0" and "1" simultaneously. When multiple qubits interact coherently, they can explore multiple options and process information in a fraction of the time it would take even the fastest non-quantum systems.

T8.7.1 Aeronautic Application

Artificial Intelligence (AI) could be described as an attempt to make machines think like humans. It is an idea that is more than 70 years old, and Airbus has long had AI applications (Figure 8.42). Airbus Helicopters has been using an artificial neural network since 2005 to adjust its rotor blades.

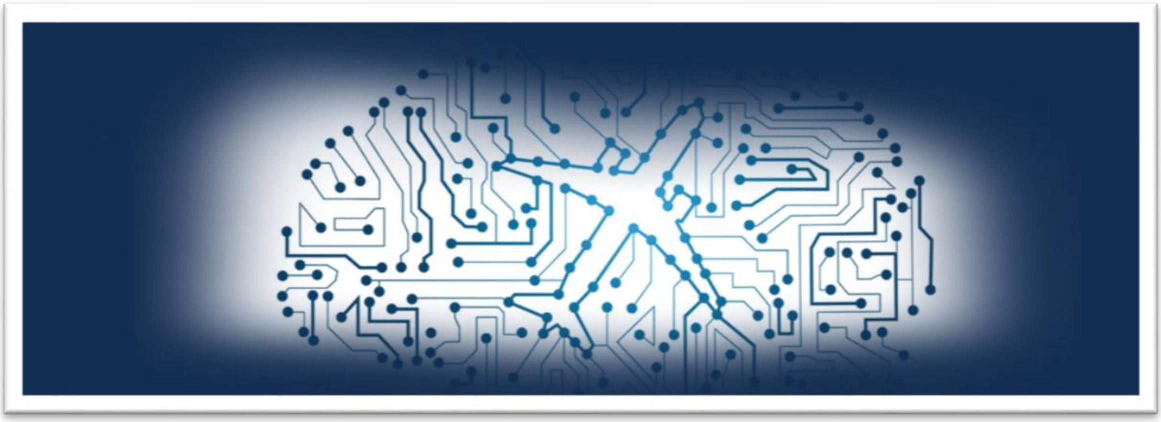


Figure 8.42 - AI and airspace

Source 7: Airbus

But now, with IBM Watson, it can process huge volumes of data and discover new, previously unknown root causes by establishing correlations that a human would never come up with. For example, Watson determined the precise relationship between the temperature and early wear of brakes. This is a completely new finding, which will allow Airbus to develop prognostics that help airlines avoid delays.

According to experts, the potential of AI for Airbus can be best illustrated using the A350 XWB as an example: the aircraft has some 50,000 sensors on board and collects 2.5 terabytes of data every day. If you let AI loose on this data, then problems and correlations can be recognised faster, and aircraft maturity can be achieved more quickly. In addition, developers inside the Airbus Group are already working on the next steps; for example, they are exploring ways in which AI can help make **UAVs** and passenger aircraft even safer.

It is possible that we will see self-flying parcel delivery UAVs in the future, if "sense and avoid" and other ATM (Air Traffic Management) issues are resolved. Moreover, passengers planes may in the future also fly with AI assisting pilots, bearing in mind that AI is best at repetitive tasks but lacks human imagination to deal with unpredictable events.

A further area where deep learning has made considerable progress is in image recognition. However, they are working on it to get the error rate of identification of these objects lower.

T8.7.2 Airbus & Quantum Computing

Rather than building a quantum computer itself, Airbus is working with academia and IT companies to define the algorithms needed to utilise the immense power of the new technology.

The company could potentially use quantum computers in digital modelling and simulation, such as the airflow over its airliners' wings or a complete airframe to improve efficiency (Figure 8.43) as a method of implementation of CFU (Computational Fluid Mechanics).

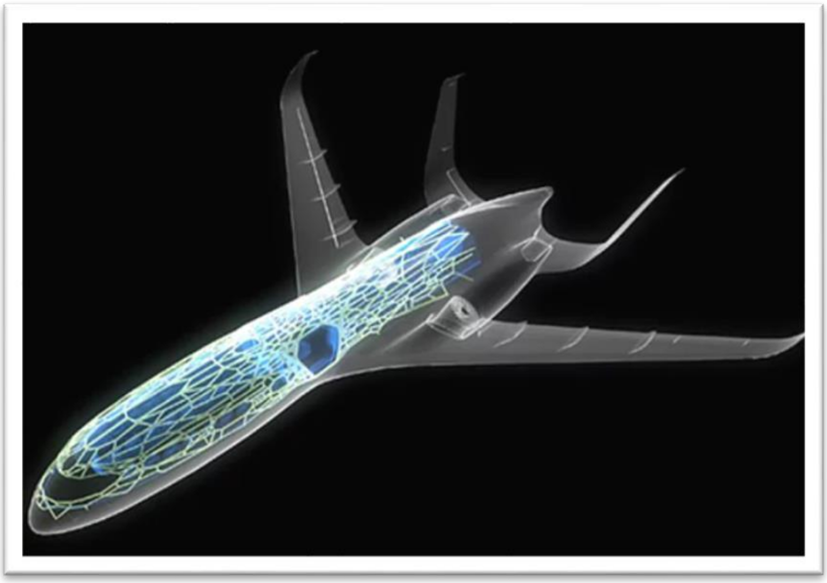


Figure 8.43 - More efficient designs of aircraft with quantum computers

Source 8: Airbus's quantum computing brings Silicon Valley to the Welsh Valleys, The Telegram

Being able to see airflows at this level of detail would allow the companies to squeeze every fraction of efficiency out of a design, potentially cutting fuel consumption, reducing drag and improving lift. In addition, the ability to stimulate new ideas at the atomic level could also speed up the development of other aircraft, including helicopters, structures and even materials.

Airbus is also sponsoring PhDs in quantum computing to help attract highly skilled people into the field. The quality of results depends both on the validity of physical models and the ability to compute them accurately.

8.7 Artificial Intelligence

Artificial intelligence has steadily developed as an academic discipline since dedicated languages like LISP and PROLOG have gained wide acceptance. Artificial Intelligence is based on a learning process whereby a large pool of repetitive experience induces a number of operating rules, procedures or interpretations. As such AI is suited to repetitive frequent events and less able to cope with isolated exceptional occurrences. The advent of big data can provide AI with the vast pools of information needed to implement learning algorithms. The competition towards autonomous or self-driving cars is one of the impetus for AI aiming to learn the habits and preferences of the individual by reference to sensor and monitoring data.

The adoption of AI techniques in one transport sector like automotive will eventually spread to other sectors like aeronautics. One of the most frequent claims about AI is that it can prevent accidents and is potentially safer than humans. In fact, this may be a double-edged sword: (i) AI is at its best in repetitive well-monitored situations for which it is trained to act without failure or the variability of humans; (ii) AI can hardly cope with unpredictable situations it was not trained for where human ingenuity could do better. Thus, the scope and domain of application of AI needs to be carefully defined to stay within its learning experience AI developed for a well-signalled road may not work on an unmarked road.

Aircraft accidents are extremely rare events for which it is difficult to train, that are best avoided by strict safety precautions, and failing that survival may depend on imaginative human action. AI could potentially be applied to all aspects of aeronautics: (i) least critical and already in use with moderate success is in fault diagnosis as part of preventive maintenance or failure detection; (ii) its extension to the pilot cockpit would likely be more controversial still than autonomous or self-driving cars in roads and city streets; (iii) its application to air traffic management (ATM) would be a step beyond full automation, which is not considered feasible at present. The application of AI in aeronautics may be gradual starting to prove itself in simpler non-safety critical situations for which other independent checks are available.

The multiple implications of artificial intelligence in the aeronautical sector (Key Topic T8.8) can be best understood from its historical evolution (Key Topic T8.9).

KEY TOPIC T8.8 IMPLICATIONS OF ARTIFICIAL INTELLIGENCE

Artificially intelligent systems currently utilize computers to emulate various faculties of human intelligence and biological metaphors. They use a combination of symbolic and sub-symbolic systems capable of evolving human cognitive skills and intelligence, not just systems capable of doing things humans do not do well. Intelligent systems are ideally suited for tasks such as search and optimization, pattern recognition and matching, planning, uncertainty management, control, and adaptation [1].

Artificial intelligence methods are applied to these control problems in which the control object cannot be adequately described by the equations of dynamics, such as differential equations, finite differences, transfer functions etc. The impossibility of adequate, accurate description can lead to failures, malfunctions, and other problems, which cannot be obtained in advance and can be assessed only in real-time operation. Thus, the intelligent control must be able to receive the information about the object, the destabilizing effect of varying operating conditions, to form conclusions, make decisions, and to stabilize the control and train.

Intelligent System (IS) applications have gained popularity among aerospace professionals due to the ease with which several of the IS tools can be implemented. In addition to this ease of implementation, IS has been shown to solve difficult problems more efficiently.

Intelligent systems are software-intensive systems that are loosely patterned after human abilities associated with learning and reasoning during adaptive planning and problem-solving. In aerospace systems and system-of-systems (SoS), intelligent systems typically take the form of autonomous systems, associate systems, or aiding systems. IS are characterized by facilities for knowledge acquisition and understanding, model-driven and evidence-based reasoning, adaptability, ability to transform data into compiled knowledge, and various forms of machine learning including supervised, unsupervised, semi-supervised, and reinforcement learning [2].

Aerospace techniques intellectualization is a current problem of scientific and technical research. This is expressed in the extension and improvement of many functions of aircraft control and taking the human operator out of the control loop through the use of artificial intelligence.

Aerospace technology intellectualization will result in [3]:

- Effective solving navigation tasks without dispatchers and navigator assistance. The concept of 4-d navigation and free flights (out of fixed routes);

- Carrying out profound diagnostics and workability recovery without ground services participation, during both flight and pre-flight;
- Implementation of several other complex facilities requiring intelligent support.

Intelligent support aims to reduce information overload, to deliver automation of aviation complex control, to supply a crew with situational awareness, to help to decide a complex environment.

Intellectualization of aerospace systems is a constructive way to improve the safety of aerospace system operation, due to the fact that the human factor is often a reason for flight incidents and accidents.

In aerospace engineering, IS come into play in a variety of mission contexts [4]. They take the form of autonomous systems for performing tasks that tend to be hazardous or that humans perform poorly [5,6]. Examples of such tasks are monitoring infrequent stimulus (i.e., low probability but potentially high consequence events), monitoring high-density events that exceed human cognitive processing ability, and operating in hazardous environments [5,6]. They take the form of associate systems to offload humans in tasks that are generally performed by humans [7]. They take the form of aiding systems for routine tasks, tasks that require perfect recall of information (e.g., viable options for a known decision situation), and tasks that require looking ahead to assess future outcomes, under different assumptions, before making decisions.

The role of humans in IS has a major impact on system architecture design and algorithm selection. When the role of the human is central to IS (i.e., human is not expected to be replaced by automation in the foreseeable future), the architecture needs to capitalize on the strengths of the human and machine respectively while circumventing their respective limitations. The primary emphasis needs to be on joint human-machine system performance. On the other hand, if the human role is not central to IS (i.e., the human is likely to be replaced by automation in the foreseeable future), then the architecture needs to be driven by performance and applicable non-functional requirements such as solution scalability, cybersecurity, resilience, and affordability.

Future intelligent systems technologies can provide increased adaptive and autonomous capabilities at all levels of autonomy. At the lowest level of autonomy, adaptation through closed-loop control and prognostics enables aerospace systems to be more resilient and intelligent by automatically adjusting system operations to cope with unanticipated changes in system performance and operating environment. At mid-level of autonomy, planning and scheduling provide capabilities to perform automatic task allocation and contingency management to reduce human operator workloads and improve situational awareness and mission planning. At high levels of autonomy, automated reasoning and decision support systems provide higher degrees of intelligence to enable aerospace systems to achieve autonomous operations without direct human supervision in the loop.

Adaptive systems are an important enabling feature common to all these levels of autonomy. Adaptability is a fundamental requirement of autonomous systems that enable a wide range of capabilities at the foundational level.

Capabilities of adaptive systems include:

- Learning and optimizing system behaviours to improve system performance and safety;
- Intelligent use of resources in aerospace processes;
- Estimate aerospace system's long term and short-term behaviours.

Machine learning techniques are commonly used in many adaptive systems. These techniques sometimes employ neural networks to model complex system behaviours. The use of multi-layer neural networks can result in non-determinism due to random weight initialization. Non-deterministic behaviours of these adaptive systems can cause many issues for safety assurance and verification and validation.

A future research goal is to develop simplified adaptive systems that reduce the introduction of non-determinism. Despite the potential benefits of neural network applications in adaptive systems, real-world experiences through recent flight research programs seem to suggest that simplified adaptive systems without neural networks may perform better in practice than those with neural networks. Simplified adaptive systems may have other advantages in that they may be easier to be verified and validated, and some existing adaptive control methods can be applied to assess the stability margins and performance of those systems.

Computational intelligence (CI) is the study of the design of intelligent agents where an agent is an entity that reacts and interacts with its environment. An intelligent agent refers to an agent that adapts to its environment by changing its strategies and actions to meet its shifting goals and objectives. The methodologies making up Computational Intelligence mostly fall under the areas of fuzzy logic, rough sets, neural networks, evolutionary computation, and swarm intelligence.

The ability to bring high-performance and efficient control to difficult problems with a far less intimate study of the physics behind the system, and thus fewer, if any, unrealistic mathematical assumptions, and constraints is the highlight of the CI tools.

The success of CI tools in limited applications opens up the imagination and enables us to boldly envision a wide variety of future aerospace applications involving numerous interactions between teams of humans and increasingly autonomous systems. An additional advantage of this class of hybrid CI approaches is that while the exploration of the solution space utilizes stochastic parameters during the learning process, once the learning system converges to a solution, the subsequent decision-making is deterministic which lends itself far better for verification and validation.

Traditional aerospace missions or scenarios tend to limit themselves when it comes to concerns about autonomous decision-making in uncertain large-scale problems. Operational doctrine development and technology advancement need to go hand-in-hand as they are far more coupled in an increasingly complex aerospace environment. A simulation-based effort may be required to enhance the “daring” and to develop confidence in the development of operational doctrines. This calls for interaction between the user and engineering communities that traditionally do not exchange much in terms of early research and exploration of ideas and exploitation of potentially powerful computational intelligent tools [8].

KEY TOPIC T8.9 EVOLUTION OF ARTIFICIAL INTELLIGENCE

In recent years, there have been several emerging technologies, which have provided benefits to various fields. However, there are several emerging trends which are expected to have a great development in the following years and other technologies which are currently being developed and have great potential. In the following image, it can be seen the Gartner Hype Cycle for Emerging Technologies (Figure 8.44) for the year 2017, in which the emerging technologies trend, which is expected to have a great development, are shown:

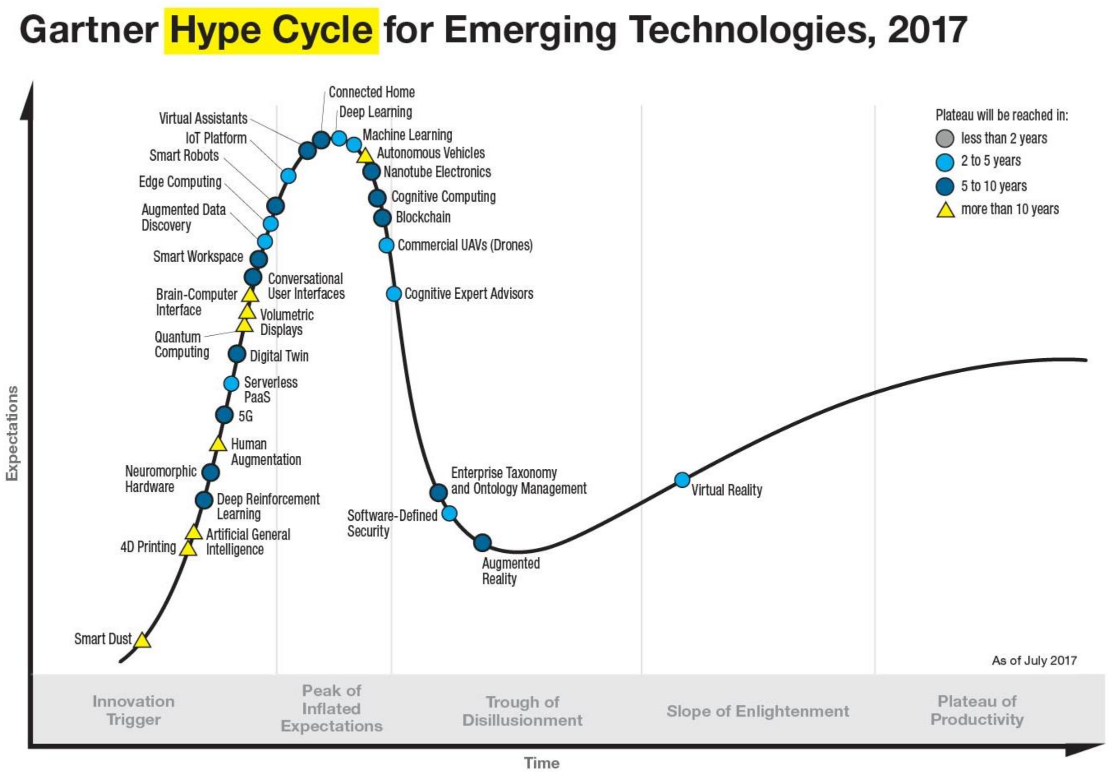


Figure 8.44- Gartner Hype Cycle for Emerging Technologies

Source 9: Gartner (July 2017)

As it can be seen in the previous picture, some of the emerging technologies which are expected to have a great development in the future are Artificial Intelligence (T8.8 – T8.9), Big data (T8.5) analytics, Quantum computing (T8.6) and Cognitive Computing (T8.7). Artificial Intelligence is considered next in more detail, starting from a historical perspective.

Artificial Intelligence (AI) is a commonly employed appellation to refer to the field of science aimed at providing machines with the capacity of performing functions such as logic, reasoning, planning, learning, and perception. Nowadays, the term AI encompasses the whole conceptualisation of a machine that is intelligent in terms of both operational and social consequences.

Current AI technologies are used in many fields such as driving, aviation, medicine and personal assistance and image recognition. An example is the vehicles known as autonomous cars. These vehicles are equipped with accurate cameras and sensors, which enable recognition of their three-dimensional environment and provides the ability to make intelligent decisions on manoeuvres in variable, real-traffic road conditions. Another example is the Alpha-Go, developed by Google Deepmind, to play the board game Go. Last year, Alpha-Go defeated the Korean grandmaster Lee Sedol, becoming the first machine to beat a professional player and recently it went on to win against the current world number one, Ke Jie, in China.

However, current AI technologies are limited to very specific applications. One limitation of AI, for example, is the lack of "common sense", that is to say, the ability to judge information beyond its acquired knowledge. A recent example is the AI robot Tay developed by Microsoft and designed for making conversations on social networks. It had to be disconnected shortly after its launch because it was not able to distinguish between positive and negative human interaction. AI is also limited in terms of emotional intelligence. AI can only detect basic human emotional states such as anger, joy, sadness, fear, pain, stress, and neutrality. Emotional intelligence is one of the next frontiers of higher levels of personalisation. True and complete AI does not yet exist. At this level, AI will mimic human cognition to a point that it will enable the ability to dream, think, feel emotions, and have their own goals. Although there is no evidence yet, this kind of true AI could exist before 2050, nevertheless the computer science principles driving AI forward are rapidly advancing and it is important to assess its impact, not only from a technological standpoint but also from a social, ethical and legal perspective.

T8.9.1 History of AI

The following image (Figure 8.45) shows a timeline, which highlights the most relevant events of AI since 1950. The blue boxes represent events that have had a positive impact on the development of AI while the red boxes represent those events with a negative impact.

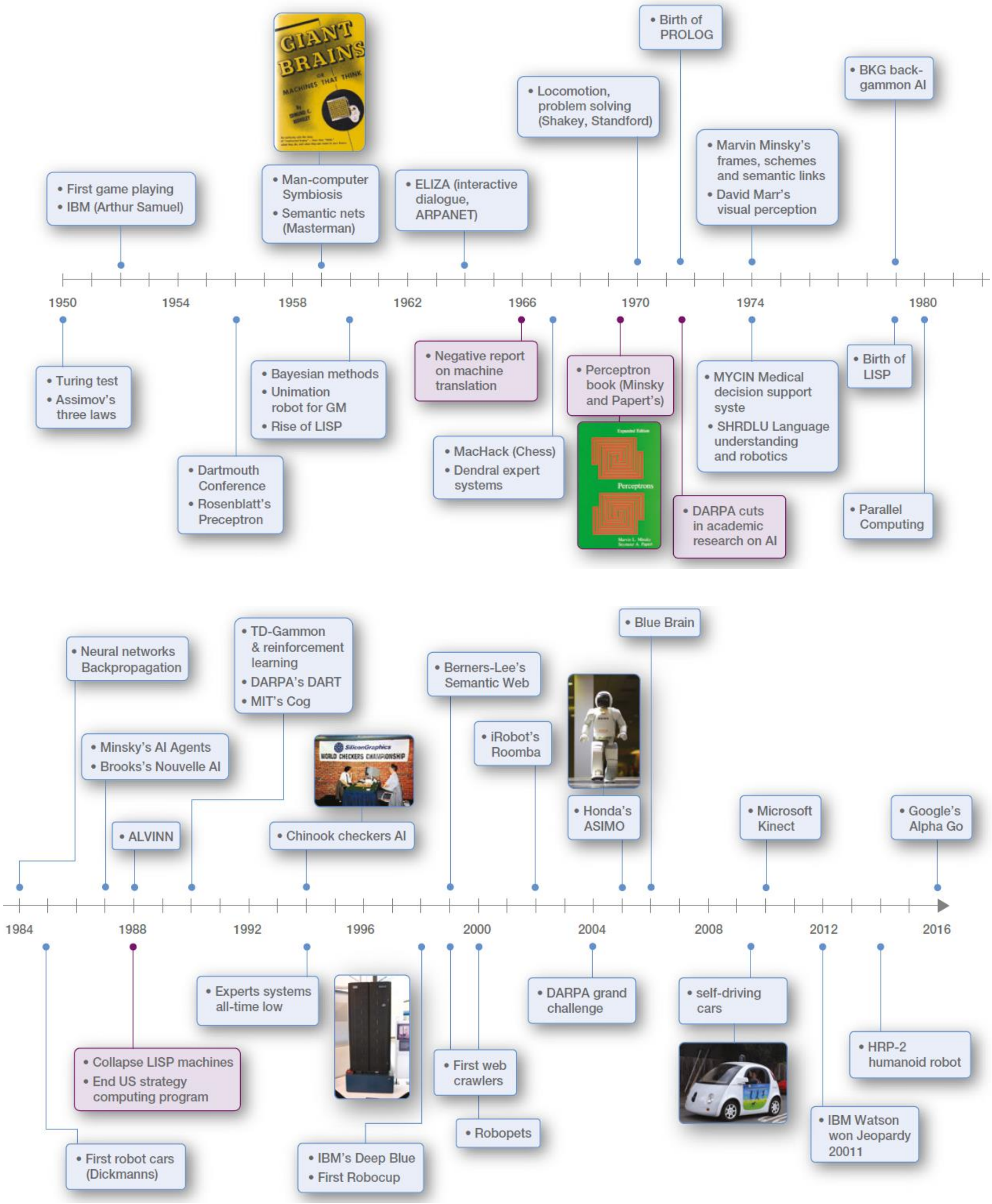


Figure 8.45– AI Timeline

Source 10: Artificial intelligence and robotics, UK-RAS network

The evolution of AI to date has endured several periods since the term AI was coined in the Dartmouth Conference of 1956. Before that, there were already advances in cybernetics and neural networks, which started to attract the attention of both the scientific communities and the public. During the 1960s, computers of the time could solve algebra and geometric problems, as well as speak English. These advances were received with optimism, however, in the 1970s the field of AI endured fierce criticism and budgetary restrictions, as AI research development did not match the overwhelming expectations of researchers. As a result, investment in AI by major agencies such as DARPA, the National Research Council and the British Government had an abrupt end and the field was stagnated for the next 10 years.

From 1980 until 1987, there was a revival of the field as AI programmes, called "expert systems", was adopted by companies and knowledge acquisition become the central focus of AI research. At the same time, the Japanese government launched a massive funding program on AI, with its fifth-generation computers initiative. However, due to the difficulty of updating and reprograming the expert systems, in addition to the high maintenance costs, they were displaced by new desktop computers developed by Apple and IBM, which had gradually improved their speed and power. In the 1990s, the new concept of "intelligent agent" emerged. An agent is a system that perceives its environment and undertakes actions that maximize its chances of being successful. The concept of agents conveys, for the first time, the idea of intelligent units working collaboratively with a common objective. This new paradigm was intended to mimic how humans work collectively in groups, organizations and/or societies. Intelligent agents proved to be a more polyvalent concept of intelligence. In the late 1990s, fields such as statistical learning from several perspectives including probabilistic, frequentist and possibilistic (fuzzy logic) approaches, were linked to AI to deal with the uncertainty of decisions. This brought a new wave of successful applications for AI, beyond what expert systems had achieved during the 1980s.

From 1997 to 2000, the field of AI was progressing behind the scenes, as no further multi-million programs were announced. Despite the lack of major funding the area continued to progress, as increased computer power and resources were developed. New applications in specific areas were developed and the concept of "machine learning" started to become the cornerstone of AI. Since 2000, with the success of the Internet and web, the Big Data revolution started to take off along with newly emerged areas such as Deep Learning. Great advances were also made in computer vision, improving visual perception, increasing the capabilities of intelligent agents and robots in performing more complex tasks, combined with visual pattern recognition. All these paved the way to new AI challenges such as speech recognition, natural language processing, and self-driving cars.

In the following years, it is expected that the rise of AI-as-a-service platforms, with lower barriers to entry, will allow companies to scale cognitive solutions in a zero-marginal cost setting and reshape industry dynamics. Moreover, while it is hard to predict the specific AI technology adoption paths over the next 10 to 15 years, the overarching impact themes are easier to envision, with AI technologies creating and changing the value proposition across all domains (Figure 8.46). Products and services will compete based on hyper-personalized, cognitive features. Firms will leverage AI to process customer preferences in real-time, so as to rapidly scale personalized products and services, as consumers become brand agnostic and more willing to pay for hyper-personalized offerings. Organizations will also become efficient hierarchies (companies typically face a trade-off between efficiency of scale and hierarchical nimbleness). Large global firms and institutions, with economies of scale that have never been unleashed due to the complex coordination required, will benefit from AI; they will use AI applications to rapidly assess, predict and simulate decisions across silos, spans and layers. Industrial companies are moving rapidly into the AI domain, investing in R&D around the "industrial internet". Analytics is being deployed for asset performance management and operations optimization, AI is improving safety and accessibility in the automotive industry and intelligent scheduling software is being adapted to real-time production variability. AI systems are enabling new levels of production system optimization, such as predictive maintenance and improved quality management. Natural language processing can be adopted to create task-specialized personal assistants, as well as platforms for conversational technologies that can be provided as a service and integrated into various applications. Computer vision capabilities enhance visual navigation for self-driving cars as well as 3D scanning. Pattern recognition can identify customer preferences and be deployed to aid drug discovery. AI reasoning and optimization technologies are penetrating the value chain in various industries, such as the automotive sector, and currently inform 75% of consumer picks on Netflix. AI is used to optimize the multi-robot fulfilment system in Amazon warehouses.

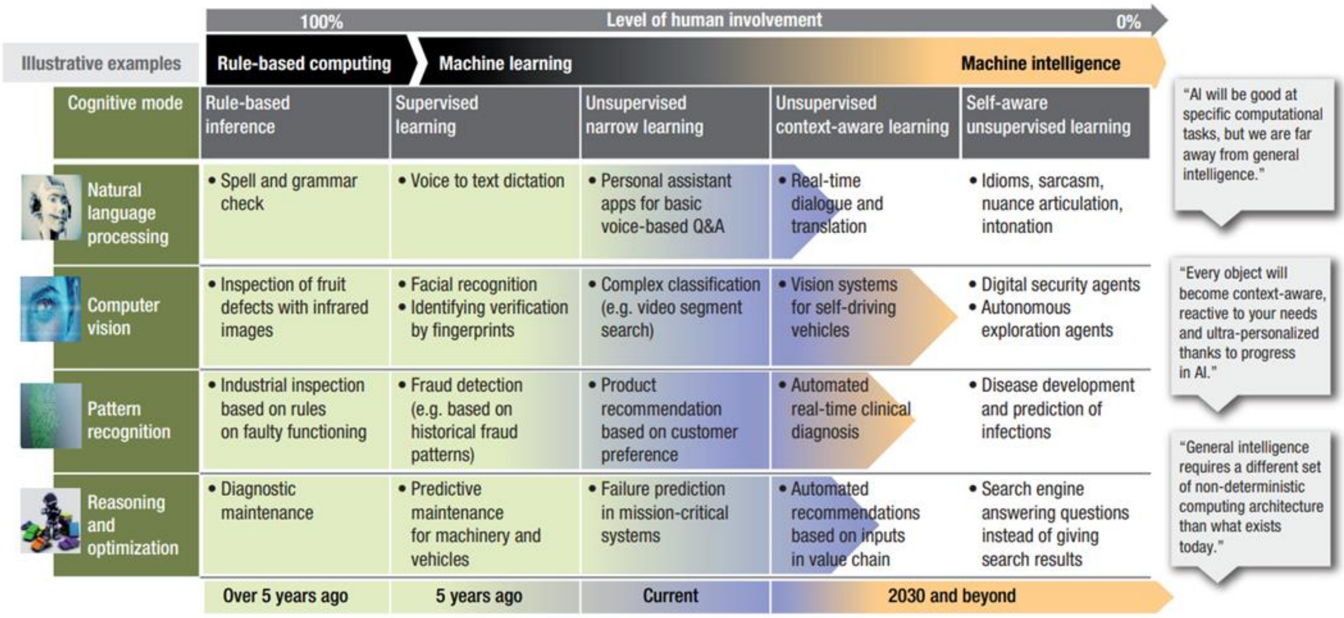


Figure 8.46 - Development of AI and its future state

Source 11: Technology and Innovation for the Future of Production: Accelerating Value Creation

T8.9.2 Financial Impact of AI

It has been well recognised that AI amplifies human potential as well as productivity and this is reflected in the rapid increase of investment across many companies and organisations. These include sectors in healthcare, manufacturing, transport, energy, banking, financial services, management consulting, government administration and marketing/advertising. The revenues of the AI market worldwide were around 260 billion US dollars in 2016 and this is estimated to exceed $3,060 billion by 2024. This has had a direct effect on robotic applications, including exoskeletons, rehabilitation, surgical robots, and personal care-bots. The economic impact of the next 10 years is estimated to be between $1.49 and $2.95 trillion. Therefore, IA is a sector with a great potential of development, as it can be seen in the next image (Figure 8.47):

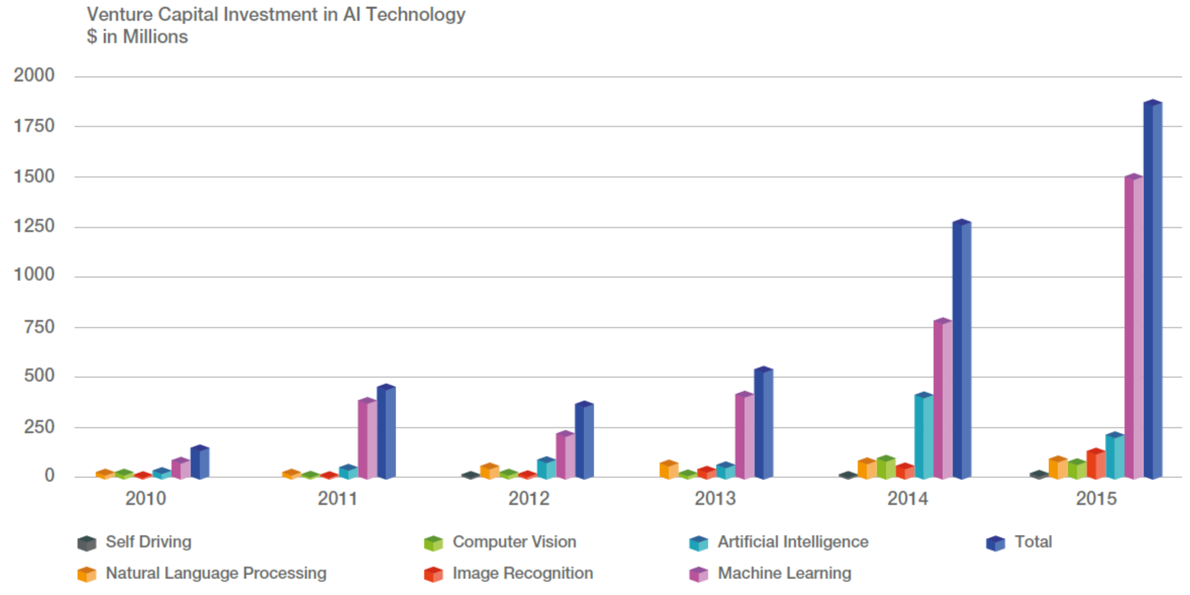


Figure 8.47 - Venture capital investment in AI technology worldwide

Source 12: Artificial intelligence and robotics, UK-RAS network

As a result, there is a huge potential for economic growth and, for that reason, major technology firms are investing in applications for speech recognition, natural language processing and computer vision. For example, companies such as Google, Microsoft, Apple, Amazon, or Facebook made between 2014 and 2015 26 acquisitions of companies developing AI technology, totalling over $5 billion costs.

In 2014, Google acquired DeepMind, a London-based start-up company specialising in deep learning, for more than $500M and set a record of company investment of AI research to an academic standard. One of the achievements of DeepMind was in developing AI technology able to create general-purpose software agents that adjust their actions based only on a cumulative reward. On the other hand, IBM has developed a supercomputer platform, Watson, which has the capability to perform text mining and extract complex analytics from large volumes of unstructured data. To demonstrate its abilities, IBM Watson, in 2011, beat two top players on 'Jeopardy!', a popular quiz show, that requires participants to guess questions from specific answers. This achievement has had a significant impact on the performance of web searches and the overall ability of AI systems to interact with humans. In 2015, IBM bought AlchemyAPI to incorporate its text and image analysis capabilities in the cognitive computing platform of the IBM Watson. The system has already been used to process legal documents and provide support to legal duties. Experts believe that these capabilities can transform current health care systems and medical research.

Research in top AI firms is centred on the development of systems that are able to reliably interact with people. Interaction takes more natural forms through real-time speech recognition and translation capabilities. Robo-advisor applications are at the top of the AI market with a globally estimated 255 billion in US dollars by 2020. There are already several virtual assistants offered by major companies. For example, Apple offers Siri and Amazon Alexa, Microsoft offers Cortana, and Google has the Google Assistant. In 2016, Apple purchased Emotient, a start-up using artificial-intelligence technology to read people's emotions by analysing facial expressions and DeepMind created WaveNet, which is a generative model that mimics human voices.

Recently, OpenAI, a non-profit organisation, has been funded as part of a strategic plan to mitigate the risks of monopolising AI. OpenAI has re-designed evolutional algorithms that can work together with deep neural networks to offer state-of-the-art performance. It is considered to rival DeepMind since it offers similar open-source machine learning libraries to TensorFlow, a deep learning library distributed by Google DeepMind. Nevertheless, the big difference between the technology developed at OpenAI and the other private tech companies, is that the created Intellectual Property is accessible by everyone.

The following Table 8.5 shows the major companies which invest in IA:

	Technology/Platforms	AI applications of significant impact
Google DeepMind	Search engine, Maps, Ads, Gmail, Android, Chrome, and YouTube	Self-driving cars: Technology that allows a car to navigate in normal traffic without any human control.
	Deep Q-network: Deep Neural Networks with Reinforcement Learning at scale.	AlphaGo: The first computer program to beat professional players of Go. DQN: Better than human-level control of Atari games through Deep Reinforcement Learning. Wavenet: Raw audio from impersonating any human voice
IBM	Manufacturer of computer hardware and software Hosting and consulting services Cognitive Computing	Deep Blue: First computer program to defeat world champion chess player Watson: Won top players on 'Jeopardy!', a popular quiz show.
Facebook	Social Networking Service	Applied Machine Learning: Spot suicidal users Human-Computer Interaction: Image Descriptions for Blind Users
Apple Inc.	Computer hardware and software Consumer electronics Online services	Siri: AI Virtual Assistant Self-driving car: AI technology that could drive a car without human interaction.
Amazon	Cloud Computing Online retail services Electronics	Alexa: AI virtual assistant Amazon AI platform: Cloud software and hardware AI tools
Microsoft	Developing, manufacturing, and licensing computer hardware and software Consumer electronics	Microsoft Azure: Cloud services Cortana: AI virtual assistant

Table 8.5 - Major companies in AI

Source 13: Artificial intelligence and robotics, UK-RAS network

As can be seen in the next image (Figure 8.48), China and the United States dominate investments in artificial intelligence. European companies including ABB, Bosch, BMW and Siemens are investing in AI, but overall Europe is behind in external Ai investment, which totalled 3$ to 4$ billion in 2016, compared with 8$ to 12$ billion in Asia and $15 to $23 billion in North America.

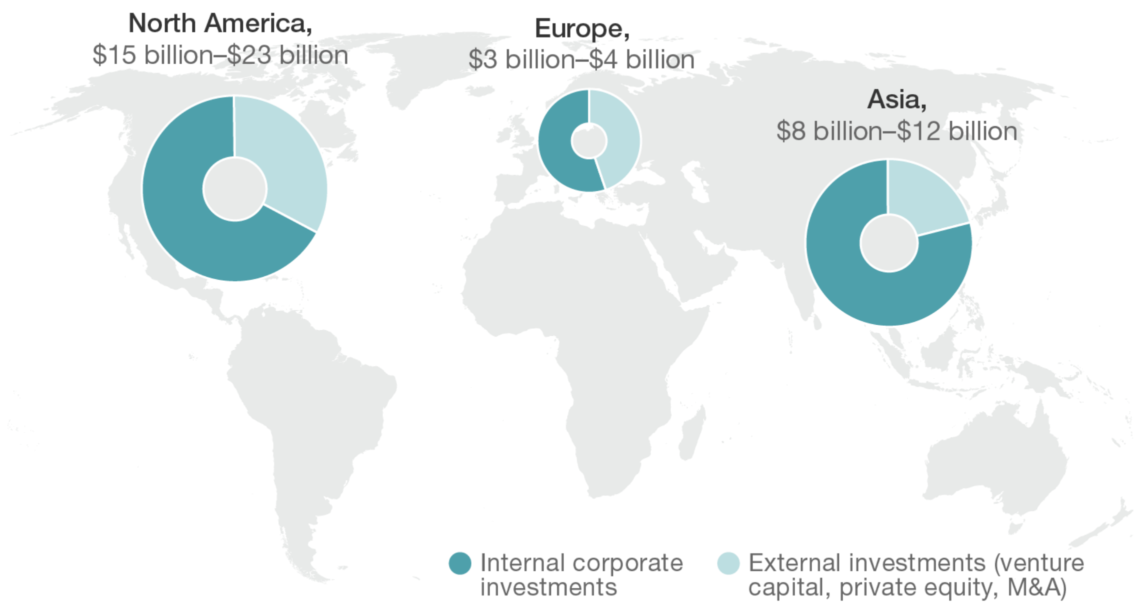


Figure 8.48 - Artificial intelligence investment in 2016

Source 14: McKinsey & Company

T8.9.3 Hardware of AI

According to Gordon Moore's prediction, the number of transistors, in a dense integrated circuit, doubles approximately every two years. This prediction has been accurate for several decades and has been used in the semiconductor industry to guide long-term planning. Today, his prediction is still valid, and the number of transistors is increasing even if, after 2005, the frequency and the power started to reduce, leading to a core scaling rather than a frequency improvement. In the future, experts believe that revolutionary technologies may help sustain Moore's law. One of the key challenges will be the design of gates in nanoscale transistors and the ability to control the current flow as, when the device dimension shrinks, the connection between transistors becomes more difficult.

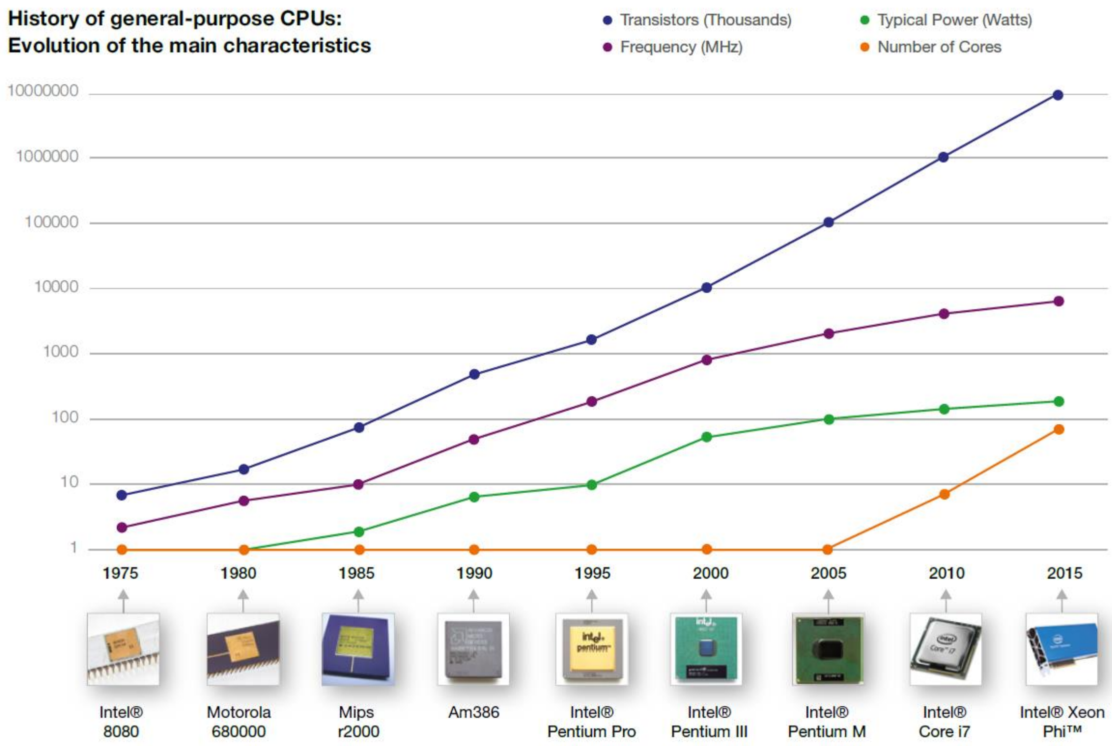


Figure 8.49 - History of general-purpose CPUs: Evolution of main characteristics

Source 15: Artificial intelligence and robotics, UK-RAS network

Modern machines combine powerful multicore CPUs (Figure 8.49) with dedicated hardware designed to solve parallel processing. GPU and FPGA are the most popular dedicated hardware commonly available in workstations developing AI systems.

- A GPU (Graphics Processing Unit) is a chip designed to accelerate the processing of multidimensional data such as an image. A GPU consists of thousands of smaller cores, intended to work independently on a subspace of the input data that needs heavy computation. Repetitive functions that can be applied to different parts of the input, such as texture mapping, image rotation, translation, and filtering, are performed at a much faster rate and more efficiently, through the use of the GPU. A GPU has dedicated memory and the data must be moved in and out in order to be processed.
- FPGA (Field Programmable Gate Array) is a reconfigurable digital logic containing an array of programmable logic blocks and a hierarchy of reconfigurable interconnections. An FPGA is not a processor and therefore it cannot run a program stored in the memory. An FPGA is configured using a hardware description language (HDL) and unlike the traditional CPU, it is truly parallel. This means, that each independent processing task is assigned to a dedicated section of the chip and many parts of the same program can be performed in simultaneously

While a GPU is designed to perform efficiently, with similar threads on different subsets of the input, an FPGA is designed to parallelize sequential serial processing of the same program.

T8.9.4 Subfields and Applications of AI

AI is a diverse field of research and it is composed of many subfields, few of them include:

- Neural Networks;
- Evolutionary and Genetic Computing;
- Vision Recognition;
- Robotics;

- Expert Systems;
- Speech Processing;
- Natural Language Processing;
- Machine Learning.

T8.9.4.1 Neural Networks

The study of Neural Networks (NNs) began with an aim to replicate the thought process of a human brain. It refers to a huge network of data sets which are interconnected and continuously sending data to each other. Artificial Neural Network (ANN) is a computational structure intended to mimic biological neural networks. It is composed of a large number of highly interconnected processing elements called neurons. The mass of an interconnection is a quantity that states the strength of the associated interconnection. The foremost representative of ANNs is its capability to study. Normally, An ANN is configured for a specific application, such as pattern recognition or data classification.

An Artificial Neural Network is specified by:

– Neuron model: the information-processing unit of the NN,

– An architecture: a set of neurons and links connecting neurons. Each link has a weight,

– A learning algorithm: used for training the NN by modifying the weights in order to model a particular learning task correctly on the training examples.

Some of their applications are:

- Character Recognition: Character recognition has become very significant as handheld devices are becoming gradually popular. Neural networks can be used to recognize handwritten characters.
- Image Compression: NNs can receive and process huge amounts of information at once, building them beneficial in image compression. With the cyber explosion and many sites using more images on their sites, using neural networks for image compression is useful.
- Stock Market Prediction: Now a day, the stock market is becoming extremely complicated. Several factors weigh in whether a given stock will go rise or fall on any given day. Meanwhile, neural networks can inspect a proportion of information quickly and grouping it all out; they can be used to forecast stock prices.
- Medicine, Security, and Loan Applications
- Weather forecasting: Neural networks are nowadays being used for predicting weather conditions. Past data is provided to the neural network, which then analyses the data for patterns and predicts the future weather conditions

T8.9.4.2 Genetic Computing

In the environment, evolution is mostly resolved by natural selection or various individuals competing for resources in the environment. Those individuals that are well adapted are more likely to survive and disseminate their genetic material. The encoding procedure for genetic information (genome) is done in a way that confesses asexual reproduction, which outcomes in children that are genetically identical to the parent. Sexual reproduction allows some exchange and restructuring of chromosomes, producing offspring that contain a grouping of information from each parent. This is the recombination operation, which is often named to as crossover because of the way strands of chromosomes cross over during the exchange. The assortment in the population is achieved by mutation operation procedure. The Genetic computing imitates this process in order to solve difficult problems.

Some of the applications of genetic computing are:

- Automotive Design: Use of Genetic Systems to both select compound materials and aerodynamic shapes for race cars and consistent means of shipping (including aeronautics) can return groupings of best materials and best engineering to deliver faster, more fuel-efficient and harmless vehicles
- Robotics: Genetic algorithms can be encoded to search for a range of optimal designs and machineries for each specific use, or to return results for absolutely new types of robots that can achieve multiple tasks and have more universal application.
- Evolvable Hardware: Hardware applications are electronic circuits which are created by genetic algorithm computer prototypes which will use stochastic (statistically random) operators to progress new patterns from old ones. Consequently, genetic algorithms would enable self-adaptation and self-repair.
- Optimized Telecommunications Routing: the genetic algorithms have been developed that will allow for dynamic and anticipatory routing circuits for networks telecommunications. They are being developed to enhance the placement and routing of cell towers for good coverage and comfort of switching.
- Invention of Biomimetic: Biomimetic is the term which indicates the development of technologies encouraged by designs in nature. Programmers of genetic algorithms are working on applications that not only to analyse the natural designs themselves for a return on how they work but also join natural designs to create something entirely new that can have unforeseen applications.
- Code breaking and Encryption: For the security front, genetic algorithms can be used both to create encryption for data as well as to break the codes.
- Computerized Molecular Design: The genetic algorithms are used to help in the understanding of protein folding, evaluating the effects of substitutions on protein functions, and to identify the binding attractions of several designed proteins industrialized by the pharmaceutical industry for better treatment of special infections.

T8.9.4.3 Vision Recognition

Computer Vision is the science and technology of gaining models, sense and control information from visual data. Computer vision can be divided into computational vision and machine vision. Computational vision takes to ensure with simply recording and exploring the visual acuity and trying to recognize it. Machine vision has to do with by means of what is found from computational vision and relating it to profit people, animals, environment, etc.

In several computer vision applications, the computers are pre-programmed to solve a certain task, but techniques based on learning are now becoming gradually common. Examples of applications of computer vision include systems for:

- Monitoring processes, e.g., Industrial robot;
- Collaboration, e.g., as the input to a device for computer-human interaction;
- Military, e.g., the discovery of enemy soldiers or vehicles and missile guidance;
- Automatic inspection, e.g., in industrialized applications;
- Agriculture process, e.g., optical sorting;
- Navigation, e.g., by an autonomous vehicle or mobile robot;
- Modelling substances or surroundings, e.g., medical image analysis;
- Support of visual effects design for cinema and broadcast, e.g., camera tracking.

T8.9.4.4. Speech Recognition

Speech recognition is one of the most innovative conceptions of electrical engineering and computer science. Essentially, speech recognition or computer speech recognition is nothing more than the approach of transforming a speech signal into the sequence of words, by the help of different systems and procedures.

Speech recognition is also stated as ASR (Automatic Speech Recognition), STT (Speech to text) or just computer speech recognition. Artificial intelligence is one of the most developing and effective techniques, which supports faultless and exact speech recognition.

AI is widely used in different areas, including prosaic signals and traffic lights, robotic household gear, conservation systems and homemade security, healthcare robotics, credit card trades, cell phones (smartphones), and video games.

- Automated identification - Australia's 8th largest insurers, ahm Health Management is effectively using speech biometrics to allow present account holders to speak to customer service representatives rapidly and securely. The company has registered more than 20,000 customers' voiceprints.
- Removing IVR menus - By announcing Natural Language Speech Recognition (NLSR), universal insurance company Suncorp substituted its original push-button IVR, supporting the customer to just say what they wanted.

T8.9.4.5. Robotics

Robotics could be an area where AI can be very beneficial. It includes mechanical, generally computer-controlled devices to accomplish tasks that necessitate extreme accuracy or monotonous or dangerous work by people. These robots also increase efficiency, as they do not need any break while working thus overcoming the inherent disadvantage of tiredness in humans.

Some of the robotics applications are the following ones:

- Galaxy Robotics - Improvement of robot systems for amorphous, uneven territory based on biologically enthused inventive kinetic energy perceptions
- Subaquatic Robotics - Development of schemes for user provision in remote-controlled underwater vehicles
- Rechargeable Mobility - Conceptions for electric vehicles, battery charge technologies, and the group of vehicle data. Prototypes for intellectual, environmentally sound, and integrated urban mobility are created.
- Logistics, Production and Consumer (LPC) - Novel systems are established which will improve handling and planning tasks, fast, self-learning image recognition, and classification to identify construction faults.
- Search and Rescue (SAR) & Security Robotics - Robots will be technologically advanced to support rescue and security personnel, mission planning and independent navigation.

T8.9.4.6. Expert systems

The first extent of Artificial Intelligence application is expert systems, which are AI suites that can create resolutions, which generally necessitate a human level of proficiency. Expert systems are possibly the furthermost simply implemented and maximum extensively used AI technology. Therefore, expert systems are machines that are trained to have total expertise in specific areas of interest. They are developed to solve the problems in niche areas. These systems use statistical analysis and data mining to solve these problems by deducing the solutions through a logical flow of yes-no questions. An expert system is made up of three parts:

- Knowledgebase: It stores all the information, rules, data, and relationships that are needed by the expert system to have total expertise in its area of interest
- Inference engine: It seeks information from the knowledge base on being presented with a query, analyses it and responds with a solution or recommendation in the way a human expert would
- Rule: It is a conditional statement that links the given conditions to the final solution

A software package called DENDRAL developed at the Stanford Research Institute in 1965 was the ancestor of expert systems. Considerably like a human chemist, it could investigate information about chemical compounds to define their molecular construction. The advanced suite called MYCIN was developed in the mid-1970s and was proficient of serving physicians in the analysis of bacteriological infections. It is regularly denoted as the first real expert system.

The spell-checking efficacy in our word processor is an expert system. It takes the role of a checker by evaluation a set of sentences, testing them against the known spelling and linguistic rules, and constructing propositions of probable modifications to the writer. Expert systems, shared with robotics, carried about computerization of the engineering process which enhanced production rate and reduced errors. A typical association line that required hundreds of persons in the 1950s now merely requires ten to twenty persons who handle the expert systems that do the work. The inventors in manufacturing mechanization are Japanese automobile industrialists such as Toyota and Honda, with up to 80% automation of the industrialized process.

The most advanced expert systems, like several other innovative technologies, are used widely in army applications. An example is the F-22 Raptor, an aircraft of the U.S Air Force. The pointing supercomputer on the team the Raptor precedes the role of a radar controller by inferring radar signals, detecting a target, and testing its radar signature against known opponent types deposited in its database.

T8.9.4.7. Natural Language Processing

Natural-language-processing software package use AI to let a user communicate with a computer in the user's natural language. The computer can both recognize and reply to instructions given in a natural language. The penalty area of Natural Language Processing (NLP) is to plan and construct a computer system that will investigate, recognize, and produce natural human-languages. Usages of NLP comprise machine transformation of one human- language text to another; group of human-language text such as literature, booklets, and universal explanations; interfacing to additional systems such as databases and robotic systems accordingly facilitating the use of human- language type commands and enquiries; and accepting human-language text to provide a summary or to appeal conclusions. One of the easiest jobs for a NLP structure is to parse a sentence to govern its syntax. A more difficult assignment is defining the semantic meaning of a sentence. One of the most challenging tasks is the analysis of the framework to determine the exact meaning and associating that with other text.

Applications of Natural Language Processing (NLP):

- Spelling amendment, syntax checking;
- Enhanced search engines;
- Information mining;
- Psychoanalysis, Harlequin passions;
- Innovative interfaces;
- Speech appreciation (and text-to-speech);
- Negotiation Systems (USS Enterprise on-board computer);
- Machine transformation (Babel fish).

T8.9.4.8. Machine Learning

Machine learning programs identify patterns in data and adjust program actions consequently. For instance, Facebook's News Feed changes according to the customer's private communications with other consumers. If a customer regularly tags a friend in snapshots, writes on his wall or likes his/her links, the News Feed will display more of that friend's movement in the user's News Feed due to assumed closeness.

Some of the applications of machine learning are the following:

- Face detection in Mobile Camera: Usually Cameras can automatically snap a photo because of developments in machine learning methods.
- Face recognition: An efficient program can identify an individual from a picture. We can find this feature on Facebook for mechanically tagging people in snapshots where they appear. Advancement in machine learning is additional accurate auto-face group software.
- Image classification: The major application of deep learning is to improve image classification or image categorization in applications such as Google photos. Google pictures would not be possible without advancements in deep learning.
- Speech recognition: Enhancements in speech recognition systems have been made possible by machine learning explicitly deep learning.

- Google: Google is a front-runner in this area because machine learning is a precise important component to its primary advertising and search businesses.
- Anti-virus: Machine learning has been used in Anti-virus software to improve discovery of malicious software on computer procedures.
- Anti-spam: Machine learning can also be used to train the best anti-spam software systems.
- Genetics: In machine learning, the classical data mining, or clustering algorithms such as agglomerative clustering are used in genetics to assist find genes associated with a particular disease.

In the next Figure 8.50 as an example, the main applications of AI are presented, which have been described in the previous points:

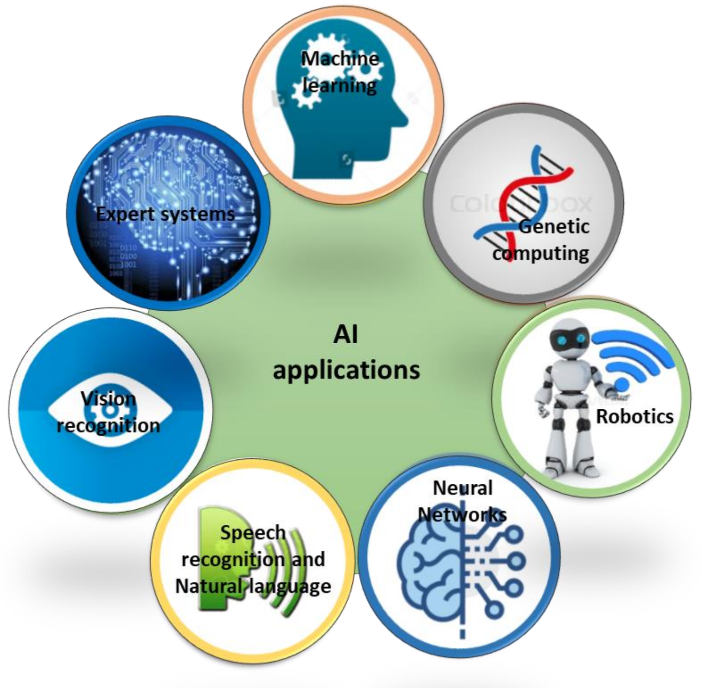


Figure 8.50 - AI applications

T8.9.5 Applications of AI in Aviation

Some existing AI use cases in aviation include:

- Flight management computer systems used in some aircraft to assist the pilot with information and for handling purposes.
- Computer systems behind the autopilot feature to steer the aircraft along a predefined trajectory without the need for pilot intervention.
- Computer systems supporting automated aircraft cabin pressurization to ensure the cabin environment is safe and comfortable for passengers.
- Analysis and prediction of passenger behaviour/demand.
- Seamless airport security processes, through facial recognition and biometrics.
- AI providing support to the optimization of revenue management, route network, fleet management, and pricing strategies.
- Self-flying planes.
- Autonomous airport processes, e.g. ground handling, loading, fuelling, cleaning, and aircraft safety checks.
- Autonomous in-flight services.
- AI assistants: responding to customer inquiries and responding to voice commands for domestic airline flight info and ticket availability through interactions using natural language.

- Facial Recognition: Facial recognition technology is being used to perform customer identity verification and to match passengers to their luggage through kiosks.
- Airplane simulators are already using AI in order to process the data taken from simulated flights. One example is aircraft warfare where computers are able to come up with the best success scenarios in these situations as these machines can create strategies based on the placement, size, speed and strength of the forces and counter forces.

In recent years, artificial intelligence technologies have developed dramatically due to improvement in the processing capacity of computers and the accumulation of big data. However, the results of current artificial intelligence technologies remain limited to specific intellectual areas, such as image recognition, speech recognition, and dialogue response. That is, current AI is a specialized type of artificial intelligence which develop the intellectual work carried out by each area of the human brain; they are only a substitute and do not perform all of the functions of the human brain. In other words, AI has not been able to cooperate with whole-brain functions such as self-understanding, self-control, self-consciousness, and self-motivation.

Despite all the IA benefits and advantages, there are still many problems to overcome before its widespread applications.

- Intelligence as a multi-component model: A machine to be called "intelligent" should satisfy several criteria that include the ability of reasoning, building models, understanding the real world and anticipate what might happen next. The concept of "intelligence" is made of the following high-level components: perception, common sense, planning, analogy, language, and reasoning.
- Large datasets and hard generalisation: After extensive training on big datasets, today machines can achieve impressive results in recognising images or translating speech. These abilities are obtained thanks to the derivation of statistical approximations on the available data. However, when the system must deal with new situations when limited training data is available, the model often fails. We know that humans can perform recognition even with small data since we can abstract principles and rules to generalise to a diverse range of situations. The current AI systems are still missing this level of abstraction and generalisability.
- Black box and a lack of interpretation: Another issue with the current AI system is the lack of interpretation. For example, deep neural networks have millions of parameters and to understand why the network provides good or bad results becomes impossible. Despite some recent work on visualising high-level features by using the weight filters in a convolution neural network, the obtained trained models are often not interpretable. Consequently, most researchers use current AI approaches as a black box.
- Robustness of AI: Most current AI systems can be easily fooled, which is a problem that affects almost all machine learning techniques.

Despite these issues, it is certain that AI will play a major role in the future. As the availability of information grows, humans will rely more and more on AI systems to live, to work and to entertain. Therefore, it is not surprising that large tech firms are investing heavily in AI-related technologies. In many application areas, AI systems are needed to handle data with increasing complexities. Given increased accuracy and sophistication of AI systems, they will be used in more and more sectors including finance, pharmaceuticals, energy, manufacturing, education, transport, and public services. In some of these areas, they can replace costly human labour, create new potential applications, and work along with /for humans to achieve better service standards. Advances in AI will also play a critical role in imitating the human brain function. Advances in sensing and computation hardware will allow linking brain function with human behaviour at a level that AI self-awareness and emotions could be simulated and observed more pragmatically. Recently, quantum computing has also attracted a new wave of interest from both academic institutions and technology firms such as Google, IBM, and Microsoft.

8.8 New Materials

Progress in materials has been a key to advances in aeronautics since its birth at least in two areas: (i) strong and light structures able to withstand flight and landing loads without demanding more than the essential lift and incurring excessive drag; (ii) high-temperature turbine blades of jet engines subject to rotational and aerodynamic loads combined with heat fluxes. The evolution from wood and canvas, to aluminium and high-strength alloys and to composites has allowed the design of larger and faster aircraft without proportional increases in empty weight, and with larger payload and fuel fractions. High-strength materials able to withstand high temperatures include alloys and ceramics and apply to all hot sections of engines, structures subject to their exhaust and high-speed flight beyond the heat barrier at Mach 2-3. The contribution of materials and structures to progress in aeronautics has been steady and gradual, e.g. a 10-30% weight saving replacing a metal wing or fuselage by a full composite one. The prospect of structures having a fraction of their current weight is brought by nanotube developments.

The development of new materials is driven both by the pull of aviation needs (Key topic T8.10) and by the progress of technologies (Key Topic T8.11). Materials research is closely related to the structures employing them (Section 8.9).

KEY TOPIC T8.10 AVIATION NEEDS OF NEW MATERIALS

T8.10.1 Introduction

Constant pressure for fuel efficiency is forcing aerospace manufacturers to find ways to incorporate new or previously impractical to machine materials. Forty years ago, aluminium dominated the aerospace industry - as much as 70% of an aircraft was made of it. Aluminium was used in any part of a plane, from the fuselage to main engine components. Materials such as titanium, graphite, fibreglass or composites and alloys were also used, but only in very small quantities.

T8.10.2 New materials

Currently, the typical airplane is constructed as little as 20% pure aluminium and most of the non-critical structural material consists of even lighter-weight carbon fibre reinforced polymers (CFRPs) and honeycomb materials. Also, for engine parts and critical components, there is a simultaneous push for lower weight, increase strength and higher temperature resistance. Those changes are made in the aim of reducing the cost of aerospace manufacture, improving fuel economy through efficiency and light-weighting. “The materials used must be lightweight, of course, but they also need to be rigid and strong enough to withstand intense mechanical stress. They also need to withstand impact from hailstones and bird strikes in the case of engine parts" said Jean-Pierre Poitevin, Vice President of Safran Composites, Safran Tech's R&T centre[1].

[1] https://www.safran-group.com/media/aerospace-materials-future-20170925

T8.10.3 Metal Alloys

Standard aerospace aluminium (6061, 7050, 7075) and traditional aerospace metals, like nickel 718, titanium 6Al4V, or stainless 15-5PH still have applications in aerospace, but currently are ceding territory to new metal alloys and components, designed to improve cost and performance (Figure 8.51). Some of those materials are not new for the industry, rather are new to practical production application, as machine tools, tooling technology and insert coatings have sufficiently advanced to tackle difficult-to-machine alloys.

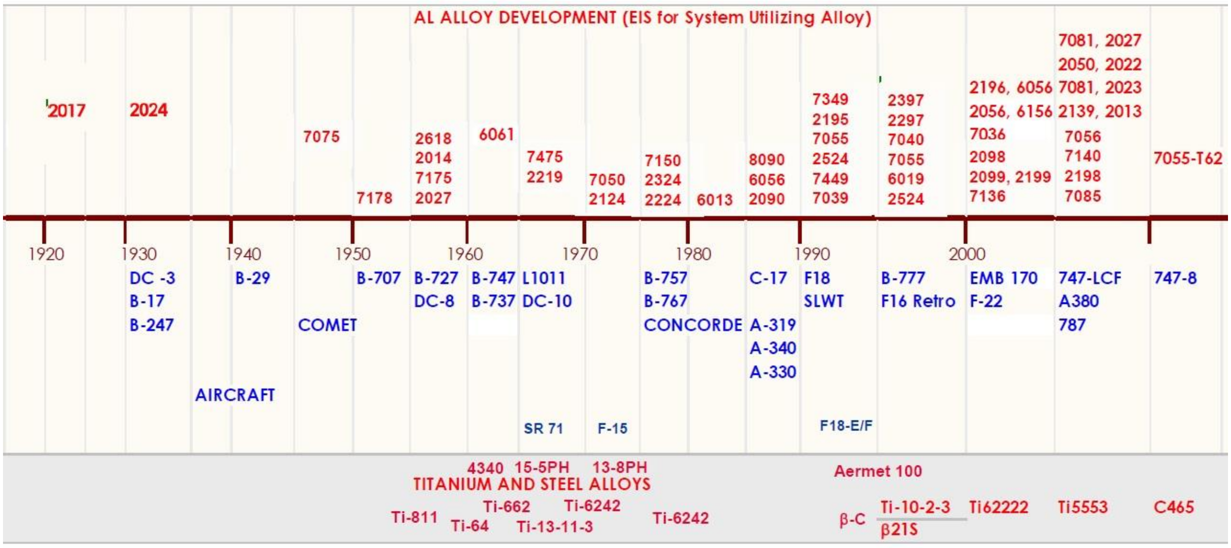


Figure 8.51 – Metal Alloys used in Aircraft

Source: The Challenge of New Materials in the Aerospace Industry, Gerould Young, 2013, Boeing Company

In some fields, aluminium is re-introduced to aerospace application in new alloys, especially in cases where the move to carbon fibre reinforced polymer (CFRP) has proved cost-prohibitive or unsuccessful. Reappearing aluminium alloys are titanium aluminide (TiAl) and aluminium lithium (Al-Li), for example, which have been around since the 1970s. Similar to nickel alloy in its heat-resisting properties, TiAl retains strength and corrosion resistance in temperatures up to 600°C. But TiAl is more easily machined, exhibiting similar machinability characteristics to alpha-beta titanium, such as Ti6Al4V. TiAl has the potential to improve the thrust-to-weight ratio in aircraft engines because it's only half the weight of nickel alloys. Case in point, both low-pressure turbine blades and high-pressure compressor blades, traditionally made of dense Ni-based super alloys are now being machined from TiAl-based alloys. General Electric uses TiAl low-pressure turbine blades on its GEnx engine, the first large-scale use of this material on a commercial jet engine – in this case in the Boeing 787 Dreamliner.

Another aluminium alloy is weight-saving Al-Li, in which the addition of lithium strengthens aluminium at a lower density and weight. Al-Li alloys' high strength, low density, high stiffness, damage tolerance, corrosion resistance and weld-friendly nature make it a good choice in commercial jetliner airframes. Airbus is using AA2050, Alcoa is using AA2090 T83 and 2099 T8E67. The alloy can also be found in the fuel and oxidizer tanks in the SpaceX Falcon 9 launch vehicle. The alloy is used extensively in NASA rockets.

Another new metal to aerospace is Titanium 5553 (Ti-5553), exhibiting high strength, lightweight, and good corrosion resistance. Major structural components that the previously used stainless steel alloys are perfect application points for this titanium alloy.

T8.10.4 Composites

Originally being used for only light structural pieces or cabin parts, composites are now increasingly being used for functional components such as engines, wing skins, and landing gear. Composites provide increased fuel efficiency because of their lightweight and are easy to handle, design, and repair. Composites are at least two materials with different properties that are combined to work together while remaining separate to a certain degree.

Due to their ability to be formed into complex shapes, composites reduce the number of heavy fasteners and joints which would be needed for metallic parts. Therefore, can be shaped into a one-piece part. Pre-formed composite components are replacing overall assemblies because industry leaders are using one-piece designs whenever they can (Figure 8.52). These designs are ultimately safer because they have fewer potential failure points.

Platform	Percent Composites	Total Wt (lbs)	Approx Composite Wt (lbs)	Approx Delivery Rate	Wt (lbs/Month)	# Delivered	Total Wt Composites Delivered (lbs)
C-17	8%	277,000	22,714	1.5		218	4,951,652
B-2	High					20	
F-18 c/d	10%	24,700	2,470			1,450	3,581,500
777	10%	300,000	30,000	7	210,000	1066	31,980,000
F-22	20%	31,700	6,340	6		339	2,149,260
F-18 e/f	18%	30,500	5,490	4	21,960	500	2,745,000
V-22	43%	33,140	14,250	1	14,250	160	2,280,000
787	50%	250,000	125,000	5	625,000	130	16,250,000
Total					871,210		63,934,360

Figure 8.52 - Use of composites in different Boeing's aircraft

Source: The Challenge of New Materials in the Aerospace Industry, Gerould Young, 2013, Boeing Company

The Douglas DC3 had a take-off weight of about 25,200 pounds with a passenger complement of about 25. With a maximum payload range of 350 miles, that is about 3 pounds per passenger mile. The Boeing 787 Dreamliner has a take-off weight of 550,000 pounds carrying 290 passengers. With a fully loaded range of over 8,000 miles, that's roughly ¼ pound per passenger mile - 1100% better[2]. Also, Dreamliner has General Electric (GEnx-1B) and Rolls Royce (Trent 1000) engine options, and both use composites extensively. In GEnx-1B composite are even used in the fan blades. In the Dreamliner power plant, composites are used for the first 5 stages of the 7-stage low-pressure turbine.

[2] https://www.thoughtco.com/boeings-787-dreamliner-820385

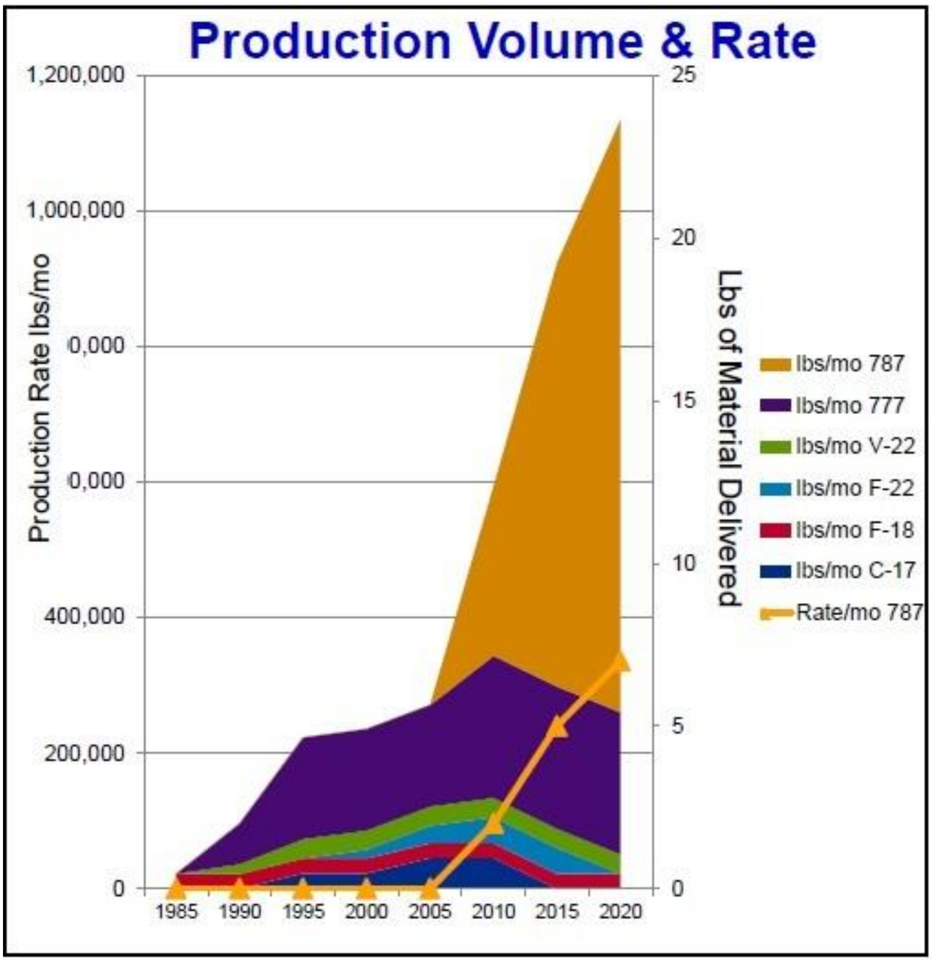


Figure 8.53 – Production Rate of Materials for aircraft programmes

Source: The Challenge of New Materials in the Aerospace Industry, Gerould Young, 2013, Boeing Company

T8.10.5 Sandwich Materials

Core materials refer to the central component of sandwich construction. Usually, a sandwich structure consists of two relatively thin, stiff, and strong faces separated by a relatively thick lightweight core, for instance, honeycomb, balsa or foam cores. The purpose of the sandwich structure is to achieve a stiff and simultaneously light component. Depending on the purpose the materials can vary, however, the most important characteristics for sandwich structures are:

- They are lightweight compared to metallic;
- Have high stiffness;
- Cost-effective compared to other composite structures.

When considering using core materials for specific applications, the production technology used for the sandwich structure is crucial, for example, wet-layup, prepreg, infusion, etc.

Honeycomb is a core used to build sandwich structure. The honeycomb, flex cores and nomex are sandwiched between two carbon skins with the purpose of creating a very stiff and strong structure. The aluminium honeycomb, for instance, is available in different aluminium grades with specific material properties and thus can be applied as required. The trend of its usage in the aerospace segment for aircraft components is increasing. The honeycomb sandwich structures are very light and a wide variety of materials can be used (e.g. carbon, paper, aluminium, etc.). Additionally, the core has a high strength to weight ratio and a very good compressive strength. The sheets of honeycomb can be available in different thicknesses and densities and can be deformed to follow the shape of the tool where the component will be laminated. The major disadvantages of honeycomb cores are price and corrosion.

T8.10.6 Foams

Composite metal foams (CMF) is a metal that is similar to a foam sponge. Heat travels slower in the air than in metal, that's why CMFs are very heat resistant. According to digitaltrends.com: "a piece of steel-steel CMF (2.5x2.5x.75 inches) was able to withstand eight minutes of 800oC heat before the entire piece of foam heated up". Standard steel would heat up in half that time. Other studies show that CMFs have incredible high-velocity impact resistance and can effectively protect against radiation. Impressively, an inch-thick piece of CMF can stop a bullet3. In tests, the bullet only left an indentation of 8mm, which is much less than the 44 mm armour indentation limit which is set by the National Institute of Justice4. CMF can be used for aircraft or space-based vehicles, which need to be protected from bits of debris travelling at high speed.

Polymethacrylimide (PMI) belongs to the family of closed-cell foams and is mainly used in high tech sandwich construction, for instance in combination with prepreg systems. The material is produced by mixing methacrylic acid and methacrylonitrile monomers. Due to its good mechanical properties, the foam core material can be processed in an autoclave, so they can cope with high pressure without collapsing. As a consequence of the overall costs involved and its performance characteristics, PMI has been used in higher performance composite parts including helicopter rotor blades, ailerons and stringer profiles in pressure bulkheads. Generally speaking, the foam core material PMI is used in the aerospace industry in a variety of structural sandwich application in either commercial, military, and general aviation aircraft, satellites and helicopters.

Polymethacrylimide main advantage:

- Lightweight;
- Strength;
- Stiffness;
- High dimensional stability;
- High fatigue life[5].

The main disadvantage of PMI is cost - in comparison to other foam cores, it is very expensive.

The industry continues to march toward components of lighter weight, increased strength, and greater heat and corrosion resistance. The mix of materials in aerospace will continue to change in the coming years with composites, freshly machinable metals, and new metals increasingly occupying the space of traditional materials (Figure 8.32).

According to Gerould Young, Director of Materials & Fabrication Technology from Georgia Institute of Technology:

- optimization will continue to increase the number of materials;
- materials improvements are vital to aircraft performance improvements;
- discovery is only a small part of materials development;
- computational materials & manufacturing tools will speed decision making;
- new material development must have:
    - reduced qualification and certification costs and schedule;

[3] https://www.digitaltrends.com/cool-tech/composite-metal-foam/

[4] https://eastbaymfg.com/new-materials-being-used-in-the-aerospace-industry/

[5] http://altairenlighten.com/in-depth/sandwich-structures/

T8.10.7 References

Safran Group, The aerospace materials of the future https://www.safran-group.com/media/aerospace-materials-future-20170925; access: February 2018.

Boeing, The Challenge of New Materials in the Aerospace Industry, Gerould Young, Director Materials & Fabrication Technology from Georgia Institute of Technology, 15th May 2013.

ThoughtCo., Boeing's 787 Dreamliner How Composites And Carbon Fibber Are Used, Todd Johnson, 2nd April 2017, https://www.thoughtco.com/boeings-787-dreamliner-820385; access: February 2018.

digitaltrends.com, Want to stop bullets and block radiation? Try this new composite metal foam, 11th April 2016, https://www.digitaltrends.com/cool-tech/composite-metal-foam/; access: February 2018.

altairenlighten.com, Sandwich structures, 7th March 2016, http://altairenlighten.com/in-depth/sandwich-structures/; access: February 2018.

KEY TOPIC T8.11 ADVANCES IN AERONAUTICAL MATERIALS

Aerospace manufacturing is unique among other volume manufacturing sectors, and this is especially true of aerospace engine manufacturing. The engine is the most complex element of an aircraft, houses the most individual components, and ultimately is an important factor in fuel efficiency. The advent of lean-burn engines, with temperature potentials as high as 3,800°F (2,100°C), has helped drive demand for these new materials, as well as cooling techniques like in-blade flows. Considering that the melting point of current super alloys is around 3,360°F (1,850°C), the challenge becomes finding materials that will withstand higher temperatures.

To meet these temperature demands, heat-resistant super alloys (HRSAs), including titanium alloys, nickel alloys, and some non-metal composite materials such as ceramics, are now being brought into the material equation. These materials tend to be more difficult to machine than traditional aluminium, historically meaning shorter tool life and less process security.

There's also a high process risk in machining aerospace parts. Because margins for error are small at 35,000ft cruising altitude, tolerances in aerospace are more precise than almost any other industry. This level of precision takes time. Longer machining times are required for each component, and more time per part makes scrap relatively expensive when factoring in time investment. Also, compared to other industries, aerospace component orders often consist of short-run quantities and long lead times, rendering scheduling for productivity, throughput, and profitability difficult.

Unlike any other industry but oil and gas, which also has high temperature, pressure, and corrosion requirements, aerospace materials themselves impact component design. Design for manufacturability (DFM) is the engineering art of designing components with a balanced approach, taking into consideration both component function and its manufacturing requirements. This approach is being applied more and more in aerospace component design because its components must accomplish certain loads and temperature resistances, and some materials can only accommodate so much. Material and component designs truly drive one another, as opposed to one following the other. This give-and-take relationship between material and design is a particular consideration when investigating next-generation materials. Aerospace manufacturers are a breed apart for all these reasons. It's not surprising that their assortment of materials is unique.

The traditional aviation material is aluminium, with an increasing variety of other materials used as replacements for higher strength, lower weight or better high-temperature resistance. Recent development of aluminium alloys has led to the re-introduction of aluminium to aerospace for example in weight-saving Al-Li, specifically designed to improve properties of 7050 and 7075 aluminium. Overall, the addition of lithium strengthens aluminium at a lower density and weight, two catalysts of the aerospace material evolution.

Titanium 5553 (Ti-5553) is another metal that is reasonably new to aerospace, exhibiting high strength, lightweight, and good corrosion resistance. Major structural components that need to be stronger and lighter than the previously used stainless steel alloys are perfect application points for this titanium alloy. Nicknamed triple 5-3, this has been a notoriously difficult material to machine – until recently. Extensive research and development have been devoted to making the metal practical to machine, and triple 5-3 has recently proven to be very predictable with machining consistency similar to more traditional titanium alloys like the aforementioned Ti6Al4V. The variances in the two materials require the use of different cutting data to obtain similar tool life. But once an operator has proper parameters set, triple 5-3 machines predictably. The key with triple 5-3 is to run a bit slower and optimize the tool path and coolant system to achieve a good balance of tool life and tool security.

Some structural pieces, like fasteners, landing gear, and actuators, require raw strength, with lightweight properties being less of a priority. In such cases, Carpenter Technology Ferrium S53 steel alloy has provided mechanical properties equal to or better than conventional ultra-high-strength steels, such as 300M and SAE 4340, with the added benefit of general corrosion resistance. This can eliminate the need for cadmium coating and the subsequent related processing.

Composite materials also represent a growing piece of the aerospace material pie. They reduce weight and increase fuel efficiency while being easy to handle, design, shape, and repair. Once only considered for light structural pieces or cabin components, composites' aerospace application range now reaches into true functional components – wing and fuselage skins, engines, and landing gear.

Also, important composite components can be formed into complex shapes that, for metallic parts, would require machining and create joints. Pre-formed composite components are not just lightweight and strong, they reduce the number of heavy fasteners and joints – which are potential failure points – within the aircraft. In doing so, composite materials are helping to drive an industry-wide trend of fewer components in overall assemblies, using one-piece designs wherever possible.

While CFRPs represent the lion's share of composite material in both cabin and functional components, and honeycomb materials provide effective and lightweight internal structural components, next-generation materials include ceramic-matrix composites (CMCs), which are emerging in practical use after decades of testing. CMCs are comprised of a ceramic matrix reinforced by a refractory fibre, such as silicon carbide (SiC) fibre. They offer low density/weight, high hardness, and most importantly, superior thermal and chemical resistance. Like CFRPs, they can be moulded to certain shapes without any extra machining, making them ideal for internal aerospace engine components, exhaust systems, and other "hot-zone" structures – even replacing the latest in HRSA metals listed earlier.

Metallic and composite materials alike continue to be developed and improved to offer ever-increasing performance, whether that's lighter weight, greater strength, or better heat and corrosion resistance. Accelerating this evolution of new materials, advances in machining and cutting technology give manufacturers unprecedented access to materials previously deemed impractical or too difficult to machine. New material adoption is happening exceptionally quickly in aerospace, requiring DFM-minded interaction between material characteristics and component design. The two must be in balance, and one can't really exist outside of the context of the other.

Meanwhile, one-piece designs are continuing to reduce the number of components in overall assemblies. In general, this bodes well for composites in aerospace, which can be formed instead of machined. A variation of this trend exists in metallic structures, as more components are conditioned in forgings to get to near-net shape, reducing the amount of machining. Elephant skins, roughed-in shapes, and thin floor sections all reduce material costs and the total number of components, but setup and fixturing continue to be challenges. Some manufacturers are turning to waterjet and other technologies to reduce or eliminate raw stock materials in need of removal. Still, difficulties exist in work holding, surface finish, and CAM tool paths. But designers, machinists, engineers, and machine tool/cutting tool partners are developing new solutions to keep the evolution churning forward.

The mix of materials in aerospace will continue to change in the coming years with composites, freshly machinable metals, and new metals increasingly occupying the space of traditional materials. The industry continues to march toward components of lighter weights, increased strengths, and greater heat and corrosion resistance. Component counts will decrease in favour of stronger, near-net shapes, and design will continue its close collaboration with material characteristics. Machine tools builders and cutting tool manufacturers will continue to develop tools to make currently unviable materials machinable, and even practical. And it's all done in the name of reducing the cost of aerospace manufacture, improving fuel economy through efficiency and light-weighting, and making air travel a more cost-effective means of transportation.

8.9 Nanotechnologies and Nanotube Structures

There is intense research on nanotechnologies, several of which have been proposed for aeronautics, such as microsensors, microactuators; some of the technologies already exist in larger scales like fluidics or piezoelectric structures or actuators with morphing capabilities to change wing, air foil or control surface shapes. A particular focus is given next to the prospects and implications of nanotube structures. Nanotube structures have a fraction of the weight of the conventional structures they replace because they are mostly hollow and consist of strategically placed nanotubes to have the same strength with a much smaller amount of material. Nanotube structures are very challenging in at least three respects: (i) they are difficult to produce since the nanotube distribution must be correct, and the tendency of nanotubes to cluster undermines total strength; (ii) the binding of nanotubes to other materials is difficult; (iii) the passage from laboratory fabrication of nanotube structures to industrial series has not been made.

Assuming that the challenges in economic serial production of nanotube structures can be overcome, their impact on aeronautics could be as significant as metallic structures, jet engines or composites. The possible revolution in aeronautics made by nanotube structures can be assessed in two cases: (a) load carrying large passenger or cargo aircraft; (b) sensor platforms with need only for small payload.

In the case (a) say of a large airliner a nanotube structure with a fraction of the weight of a conventional structure would imply that most of the take-off weight would be passengers/cargo and fuel. Assuming that 20% of the weight of a current aircraft is passengers/cargo, 30% fuel and 50% structure, with a nanotube structure weighting 1/5 or 10%, the take-off weight minus fuel would be 30% less weight means less lift, less drag, less thrust and less fuel. Thus, the fuel load could probably be halved to 15% for a total take-off weight of 45% compared with a conventional aircraft with the same payload-range. Halving the weight, lift, drag and thrust would halve fuel consumption, cost and emissions and reduce noise.

In the case (a) of an airliner or cargo aircraft, the benefit of a structure having a fraction of the weight is limited by the fixed payload weight. In the case (b) of a sensor aircraft with a light payload say 10%, fuel might be 30% and structure 60% of the total take-off weight. A nanotube structure with 1/5 of the weight would be 12% or 22% take-off weight not including fuel. Contemplating an aircraft with one-third of the weight, lift, drag, thrust and fuel consumption the total take-off weight would be 32% of a conventional aircraft for the same mission.

In rough terms, the replacement of a conventional by a nanotube structure would reduce the weight of an aircraft for the same mission to one-half for a passenger/cargo airplane and to one-third for an observation drone. This would have multiple benefits: (i) improved economics through lower fuel cost; (ii) fewer emissions due to lower fuel consumption; (iii) less demand for aviation fuel or alternative sources, reducing from 10% of the world needs to less than 5%; (iv) less engine noise at airports due to lower thrust; (v) less airframe noise due to less lift and lower landing weight; (vi) easier to reach silent operation outside airport boundaries.

The weight saving of nanotube structures could be used alternatively: (b) to increase the fuel load of an observation drone for much greater range and/or speed; (a) to increase the payload-range of a passenger or cargo aircraft. One of the main limitations of the design of structures is their own weight, such as the bending moment at the root of a wing of large span. A nanotube wing would be a fraction of the weight for the same span with a smaller bending moment at the root and lighter wing box structure. Or more interesting the same wing root bending moment would allow a larger span and better lift-to-drag ratio within aero elastic limits. Thus, the large weight benefits of nanotube structures could be used in several ways to increase aircraft efficiency.

Nanotube structures (Key Topic T8.1.3) are just one of the multiple areas of aeronautics in which nanotechnologies can have a major impact (Key Topic T8.12).

KEY TOPIC T8.12 RELEVANCE OF NANOTECHNOLOGIES TO AERONAUTICS

There are few industries where the applications of nanotechnology are as clearly beneficial as in the aerospace industry. The primary development goals match almost exactly with the advantages offered by using various nanomaterials in the place of traditional bulk metals like steel. The aerospace industry is one of the most important heavy industries in the world. Countless companies rely on the ability to ship products and people around the world with the speed that can only be achieved by air.

Along with this huge economic value, however, comes huge consumption, and one of the largest carbon footprints on the planet relative to the size of the market. For this reason, the major drivers in current aerospace R&D are towards lighter construction materials and more efficient engines - the overall goal being to reduce fuel consumption and carbon emissions associated with air travel and air freight. The significant interest in nanotechnology for the aerospace industry is justified by the potential of nanomaterials and nanoengineering to help the industry achieve this goal.

Bulk metals with some nanoscale structure are already widely used in aircraft manufacturing. It is now well known that nanostructured metals - exhibit considerably improved properties compared to their counterparts with microscale or larger grain structure. This is particularly noticeable for properties which are crucial for materials used in aircraft - primarily yield strength, tensile strength and corrosion resistance, coupled with a low density which helps keep the total weight of the aircraft down.

Various nanomaterials have been used as filler materials to enhance the properties of structural and non-structural polymers used in aircraft construction. The most commonly used nanomaterials include nano-clays, carbon nanotubes, nanofibers, and graphene. Carbon nanotubes, in particular, have been shown to give excellent advantages when used as fillers in various polymers, due to their exceptional stiffness, toughness, and unique electrical properties.

Nanocomposites typically have superb weight-to-strength ratios, and enhanced resilience to vibration and fire, making them ideal for use in the aviation industry. The properties of the nano-fillers, like the conductivity of nanotubes, for example, can create interesting opportunities for multifunctional materials. The properties of polymers enhanced by nanomaterial fillers are so well-tuned to the requirements of aircraft manufacturers, that they are, actually, being used to replace some of the metals used in the airframes. This obviously brings along huge weight savings, and often cost savings as well.

Another major trend in the materials used in aircraft is towards nano-coatings to enhance the durability of metals. In particular, magnesium alloys, which are far lighter than steel or aluminium, are prone to corrosion, due to the high chemical reactivity of magnesium. Coatings can help prevent corrosion, but the type typically used contain chromium complexes which are a highly toxic pollutant. Materials used for these novel anti-corrosion nano-coatings include silicon and boron oxides, and cobalt-phosphorous nanocrystals.

Nano-coatings are also now being used on turbine blades and other mechanical components which must withstand high temperatures and friction wear. Tribological coatings can drastically lower the friction coefficient and improve resistance to wear - this greatly improves the efficiency of the engines. Many nanostructured and nanoscale coating materials have been suggested as possible friction modifying agents, such as carbides, nitrides, metals, and various ceramics.

To conclude, the drive for lighter and more efficient air vehicles has led to the rapid adoption of nanotechnology in aerospace manufacturing. The main roadblock, as with many industries looking to adopt nanotechnology, is caused by uncertainty over the environmental and health and safety implications of these materials. Whilst nanomaterials can often be less toxic than the current materials used, the effects of long-term exposure to these novel materials are still uncertain. The potential of nanotechnology in the aerospace industry cannot be denied, however. Outside of airframe and component materials, nanotechnology applications have been found in lubricants, fuel, adhesives, and many other areas. Nanotechnology is also helping engineers to create vehicles with the necessary properties to endure the harsh conditions of space. Large scale manufacture of nanomaterials with repeatable, certifiable properties is also challenging since some laboratory techniques do not scale up readily. For example, the tendency of nanotubes to cluster reduces their potential benefit in strength-to-weight ratio.

KEY TOPIC T8.13 DEVELOPMENTS IN NANOTUBES

Composite components based on Carbon Nano Tubes (CNT) offer improved corrosion resistance and lighter weight, which improve fuel efficiency and reduce carbon dioxide emission in airplanes. The Figure 8.54 depicts and shows an overview of the actual use of composites which now constitute more than 25% of the Airbus A380 and 50% of the Boeing 787 aircraft. The panelling and aesthetic interiors consist of these new materials which reduce the overall weight of the plane by as much as 20 percent compared to aluminium-bodied planes.

Gulfstream has incorporated increasing levels of composite materials into its aircraft design. In 2007, Gulfstream initiated the Advanced Composites Research and Development program to exploit the advantages of composite structures. In 2012, this program was expanded to include new forming processes, additive manufacturing (3-D printing) and green technologies to its research and development activities.

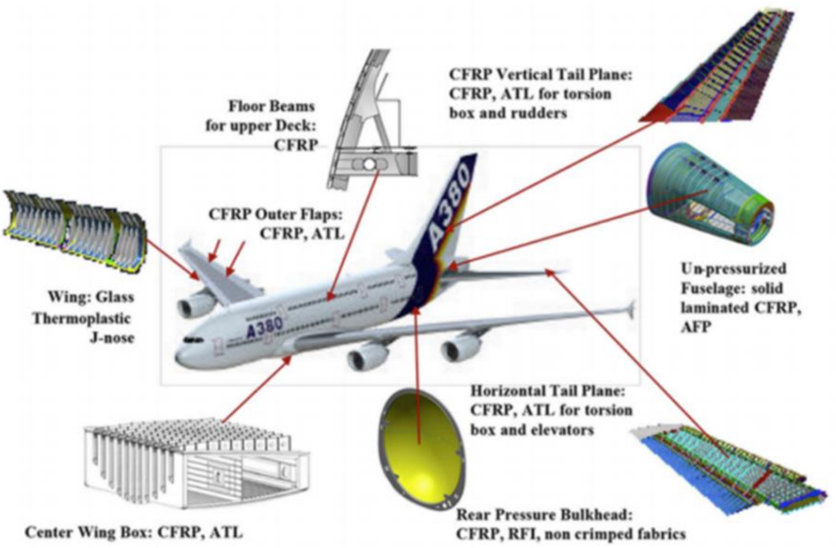


Figure 8.54 - The use of composites in Airbus A380

Source: X. Zhang et al. Recent advances in the development of aerospace materials. Progress in Aerospace Sciences 97 (2018) 22–34
https://doi.org/10.1016/j.paerosci.2018.01.001

One problem to be faced when using polymer nanocomposites is the low electrical conductivity. In fact, airplanes get struck by lightning frequently. Modern composites are reinforced with conductive metal fibres or metal screen in order to conduct away lightning currents. However, these solutions add additional weight which partially reduces the advantage related to the use of the composite systems. For this reason, a relevant research topic for nanostructured materials is focused on the improvement of the electrical conductivity.

Another issue involved in the application of CNT is depicted in the Figure 8.55 which illustrates a way to bond composite layers leading to a material substantially stronger and more resistant to damage than other advanced composites. Carbon nanotubes having a diameter of about 10 nanometres (nearly a million times smaller than the carbon fibres adopted to reinforce the polymeric resin adopted in aeronautic composite structures) exhibit a surface area 1000 times larger than that of carbon fibres leading to better bonding with the polymer matrix. The technique integrates a scaffold of carbon nanotubes within a glue-like polymer matrix. The nanotubes are vertically aligned and transferred onto a sticky, uncured composite layer. This structure is repeated to generate a stack of 16 composite plies.

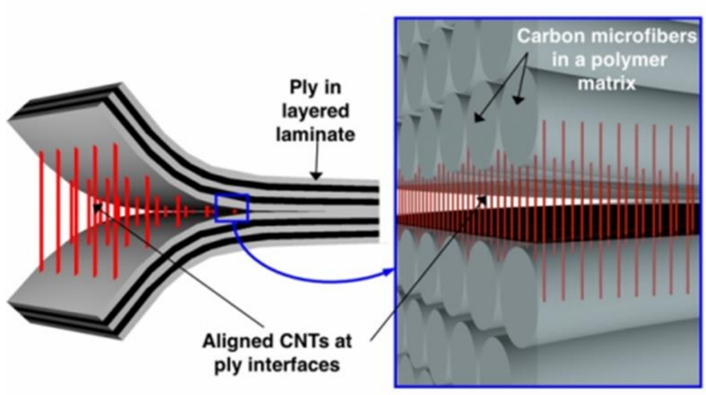


Figure 8.55 - Method to reinforce the composite systems adopted to manufacture structural parts of airplanes; Source: https://phys.org/news/2016-08-methodcarbon-nanotubes-airplane-lighter.htm

The resulting composite material is able to withstand 30 percent more force before cracking. Finally, the strength enhancements suggest this material will be more resistant to any type of damaging events or features hence good candidate as new composites to improve aircraft structural performance.

Concerning such issues, the European Union (EU) has promoted progress by supporting research efforts. In particular, through the funding of several large-scale 'flagship' projects in micro-nano-manufacturing EU, has provided an impulse for some substantial improvements in aircraft design, development, verification and validation processes.

In this regard, during FP7 several relevant projects were developed of new nanomaterials to improve different aspects connected to the challenges of the FlightPath2050. The main project objectives and results are summarized in the sequel.

IAPETUS - Innovative Repair of Aerospace Structures with Curing Optimization and Life Cycle Monitoring Abilities

- (https://cordis.europa.eu/project/rcn/91015_en.html)
- Project ID: 234333
- Funded under: FP7-TRANSPORT
- Dates: From 2009-06-01 to 2012-12-31, closed project
- Total cost: EUR 3 342 226,23; EU contribution: EUR 2 339 595
- Coordinated in: Spain
- Topic(s): AAT.2008.1.1.2. – Aerostructures; AAT.2008.1.2.2. - Maintenance and Disposal
- Funding scheme: CP-FP - Small or medium-scale focused research project

In IAPETUS two novel methodologies to repair a crack or a defect in an aircraft structure has been developed. The team used a multi-functional repair solution that includes innovative materials, i.e. smart composite repair patches made of carbon fibre (graphite) epoxy system with matrix materials containing carbon nanotubes, which improves the homogeneity of thermal and electrical properties to facilitate homogeneous heating. The innovative features derived from their novel curing methodologies, i.e. conductive heating (relies on the passage of electrical current) and induction heating (relies on the application of a magnetic field through the electrically conductive carbon nanotubes). Moreover, using a sensor technology, which they developed such as wireless impedance monitoring and infrared thermography, the team developed a new generation of adhesives with carbon nanotube additives for improved control of thermal expansion and higher electrical and thermal conductivity. The composite developed by the team of this project provides a better solution to repair the composite with reduced time and costs and is able to ensure continuous health monitoring. In this way, should a defect appear, maintenance will be timely and cost-efficient while ensuring the safety of airline passengers.

POCO - Carbon Nanotube Confinement STRATEGIES to develop Novel Polymer Matrix Composites

- (https://cordis.europa.eu/project/rcn/88797_en.html)
- Project ID: 213939
- Funded under: FP7-NMP
- Dates: From 2008-11-01 to 2012-10-31
- Total cost: EUR 8 234 036,40 EU contribution: EUR 5 524 450
- Coordinated in: Spain
- Topic(s): NMP-2007-2.1-1 - Nanostructured polymer-matrix composites
- Funding scheme: CP-IP - Large-scale integrating project

The main objective of the POCO project was to get innovative polymer composites filled with Carbon Nano Tubes (CNT) with tailor-made and superior properties for application in different industrial sectors including aeronautics. In particular, the project was focused on the selection of the best combination (according to the application) of the polymeric matrix and CNT, the study of the interface CNT/polymer characteristics and the determination of the most suitable approaches for chemical functionalization of CNT in order to achieve a proper dispersion of the nanotubes into the polymer matrix during processing and optimization of the performance. According to the reports, the project has achieved different strategies of functionalisation, alignment and positioning of CNTs, with the use of ionic liquids (ILs) as a strategy to disperse and functionalized CNTs. Moreover, successful nano-structuring and confinement of functionalised CNTs in the correlating phase block copolymers (BCs) as well as nano-structuring of thermosetting matrices was also achieved. Different properties of CNTs and nanocomposites were studied together with the influence of CNTs as a nucleating agent for crystallinity of semi-crystalline matrices. The main problems for the processing of carbon-fibre-reinforced polymer (CFRP) epoxy composites containing CNTs using different strategies has been also dealt with. However, these promising results would require further upscaling of the devices and processes to be applied at industrial level.

SARISTU - Smart Intelligent Aircraft Structures

- (https://cordis.europa.eu/project/rcn/100047_en.html)
- Project ID: 284562
- Funded under: FP7-TRANSPORT Smart Intelligent Aircraft Structures
- Dates: From 2011-09-01 to 2015-08-31, closed project
- Total cost: EUR 50 712 428,33 EU contribution: EUR 32 434 311
- Coordinated in: Germany
- Topic(s): AAT.2011.4.4-3. - Integrated approach to smart airframe structures
- Funding scheme: CP-IP - Large-scale integrating project

The SARISTU project aims at reaching a reduction of the manufacturing and operational cost of civil airliners and an enhancement of aerodynamic performance by the use of a combination of technologies based on self-sensing structures and nanocomposites. In particular, the shape adaptation (morphing) of some parts (e.g. winglet) of the external wing is addressed on a full-size by considering integrated shape sensing system to ensure optimal control of the aerodynamic surface and failure tolerance and robustness. The integration of different materials including CNT-based nanocomposites for the wing may lead to a 6 % reduction in drag, meaning that less fuel is needed. Moreover, an elastic connecting element for closing the gap between the flap and the fixed aircraft has been developed. Such innovative elastic component is based on a resin containing carbon nanotubes. The nanocomposite systems developed in this project may lead also to a weight reduction of up to 3 % when compared to traditional materials.

IASS - Improving the Aircraft Safety by Self-Healing Structure and Protecting Nanofillers

- (https://cordis.europa.eu/project/rcn/103705_en.html)
- Project ID: 313978
- Funded under: FP7-TRANSPORT
- Dates: From 2012-09-01 to 2015-08-31
- Total cost: EUR 3 270 839; EU contribution: EUR 2 397 266
- Coordinated in: Italy
- Topic(s): AAT.2012.3.4-2. - Maintenance
- Funding scheme: CP-FP - Small or medium-scale focused research project

The main objective of the IASS Project was to develop multifunctional self-healing composite for aeronautic applications. The multifunctional composite systems are developed with the aim of overcoming serious drawbacks of the composite materials and in particular the low electrical conductivity, the rather weak impact damage resistance and the poor flame resistance.

The IASS project aimed at developing all functionalities integrated into a single material able to face such important requirements of structural materials for primary structures in aeronautics. The strategy to achieve such goals relies on the use of nanotechnology for the production of new, high performance structural multifunctional materials. In order to obtain high mechanical and electrical performance, the IASS consortium led by a group of the University of Salerno (UNISA, Italy) selected multi-wall carbon nanotubes (MWCNTs). These nanomaterials were embedded inside an epoxy matrix with a particular formulation which has proven to be very effective for improving nanofiller dispersion due to a decrease in the viscosity. In addition, it has been found that the so obtained nanocomposite system is able to reduce the moisture content, which is a very critical characteristic for aeronautic materials.

As an outcome of the IASS project multifunctional carbon fibre reinforced panels (CFRPs) have been manufactured using the multifunctional resin. CFRPs (impregnated using the resin with all functionalities integrated) have been manufactured by Resin Film Infusion (RFI) using an unusual technique to infuse a nano-filled resin into the carbon fibre dry preform. In this process, a dry carbon fibre preform is placed in a vacuum bag and the resin is injected from an edge of preform while in the other is venting the vacuum so the resin fow throw the length of the preform. The scheme of the RFI is depicted in Figure 8.56, whereas, in Figure 8.36 the steps for the preparation of the laminates is illustrated. In particular, the edges of the preform are sealed to force the resin to flow only through the thickness (Figure 8.57A). The laminate is covered by a porous film and a distribution medium to allow to the resin to escape from the upper side and a breather media to receive the excesses of the resin (Figure 8.57B). Finally, the obtained compound is placed in a vacuum bag and the laminate is transferred into the autoclave (Figure 8.57C).

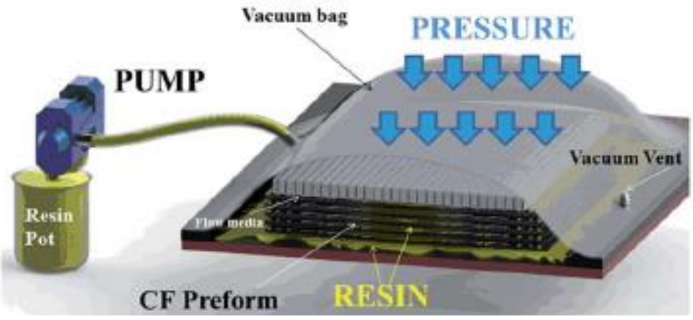


Figure 8.56 - Approach to Resin Film Infusion adopted in the IASS project
Source - L. Guadagno et al. RSC Adv., 2015, 5, 6033, DOI: 10.1039/c4ra12156b

Figure 8.57 - Steps for the preparation of laminates adopted in the IASS project
"Source - L. Guadagno et al. RSC Adv., 2015, 5, 6033, DOI: 10.1039/c4ra12156b

Flat panels have been produced and tested with respect to all functionalities. An optical picture of the manufactured panels (30 x 30 cm) is shown in Figure 8.58.

7 PLIES (BIDIRECTIONAL CARBON FIBERS FABRIC)

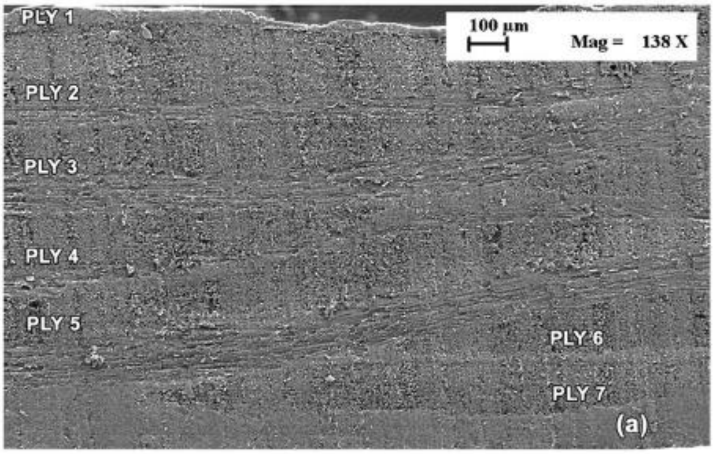


Figure 8.58 - Optical image of the CFRP panel with the epoxy based MWCNT composite developed in IASS project; Source - L. Guadagno et al. RSC Adv., 2015, 5, 6033, DOI: 10.1039/c4ra12156b

The electrical conductivity was found to be about $2x10^{4}$S/m in the direction parallel to the fibres and greater than 3.0 S/m in the direction orthogonal to the fibres. These values are among the highest values available for nanofilled resins impregnating carbon fibres. The panels also revealed enhanced flame resistance properties (Ignition time about 81 s). Furthermore, due to the auto-repair ability, a significant decrease in the fatigue crack growth rate by approximately 80% was found.

Prepreg with modified and charged epoxy resin have also been developed. The fabrication of the aeronautical prepreg demonstrators was carried out following the aeronautical standards I+D-P-233 from Airbus ("Manufacture of composite structures with carbon fibre"). Two final demonstrators have been produced: a flat panel with three T shape stringers, manufactured by infusion, and a curved panel with two omega shape stringers, manufactured by ad hoc prepreg.

In successive works, the researchers of UNISA have proposed to integrate within the CFRP panels also a stress sensor obtained with the same MWCNT-loaded composites able to detect stress levels and small damages. The Figure 8.59 shows the relation between the mechanical behaviour (i.e. σ, left vertical axis) and the normalized change of electrical resistance (i.e. $\Delta R/R0$, observed in tensile stress as a function of the axial strain (ε) and vs. time for cycling tension loading of nanocomposites.

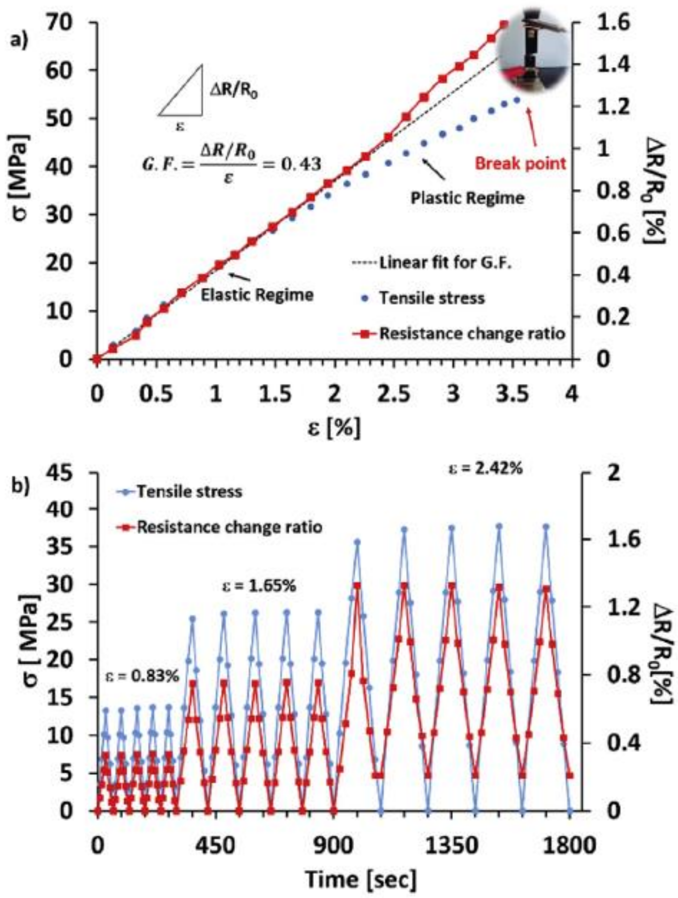


Figure 8.59 - a) Mechanical behaviour; b) normalized change of electrical resistance

Source - L. Vertuccio et al. "Piezoresistive properties of resin reinforced with carbon nanotubes for health-monitoring of aircraft primary structures", Composites Part B 107 (2016) pp. 192-202, http://dx.doi.org/10.1016/j.compositesb.2016.09.061

Looking ahead, in order to reach and retain the global leadership and the competitiveness of European Aeronautics and pave the way on achieving the demanding goals of the Flightpath 2050 for Aeronautics, the continued development of innovation and breakthrough nanotechnologies represents an indispensable need. The results obtained so far represent the reference to measure future achievements.

REFERENCES

[1] M. Hepperle, Electric Flight – Potential and Limitations, NATO Workshop Energy Efficient Technologies and Concepts of Operation STO-MP-AVT-209, 2012, DOI10.14339/STO-MP-AVT-209

[2] Roland Berger GmbH, Report Aircraft Electrical Propulsion – The Next Chapter of Aviation? 2017

[3] https://en.wikipedia.org/wiki/Eviation_Alice#/media/File:Eviation_Alice.png

[4] B. Omar, chapter Experimental studies of using a PEMFC/battery hybrid system to power small UAVs, in Energy and Sustainability V (ed. by, H.H. Al-Kayiem, C.A. Brebbia, S.S. Zubir) WIT Press, 2015, p. 273 -

[5] FhG IFAM, Li-battery roadmap - http://www.isi.fraunhofer.de/de/competence-center/neue-technologien/projekte/bema2020-batterie2020.html.

[6]https://www.researchgate.net/publication/323176008_Mass_Production_Cost_Estimation_of_Direct_H2_PEM_Fuel_Cell_Systems_for_Transportation_Applications_2017_Update

[7] https://www.aurora.aero/odysseus-high-altitude-pseudo-satellite-haps/

[8] M. Keim, J. Kallo, K.A. Friedrich, C. Werner, M. Saballus, F. Gores, Multifunctional fuel cell system in an aircraft environment: An investigation focusing on fuel tank inerting and water generation, Aerospace Science and Technology, 29 (2013) 330-338

[9] X. Zhang et al. Recent advances in the development of aerospace materials. Progress in Aerospace Sciences 97 (2018) 22–34 https://doi.org/10.1016/j.paerosci.2018.01.001

[10] R. Guzman de Villoria et al. In-plane strength enhancement of laminated composites via aligned carbon nanotube interlaminar reinforcement, Composites Science and Technology (2016). DOI: 10.1016/j.compscitech.2016.07.006

[11] Guadagno et al., Effective formulation and processing of nano-filled carbon fibre reinforced composites. RSC Adv., 2015,5, 6033, DOI: 10.1039/C4RA12156B

[12] Guadagno et al., Correlation between electrical conductivity and manufacturing processes of nano-filled carbon fibre reinforced composites, Composites Part B 80 (2015), pp. 7-14 https://doi.org/10.1016/j.compositesb.2015.05.025

[13] L. Vertuccio et al. "Piezoresistive properties of resin reinforced with carbon nanotubes for health-monitoring of aircraft primary structures", Composites Part B 107 (2016) pp. 192-202 http://dx.doi.org/10.1016/j.compositesb.2016.09.061.

[i] B.D. James, 2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles, https://www.energy.gov/sites/prod/files/2018/04/f51/fcto_webinarslides_2018_costs_pem_fc_autos_trucks_042518.pdf

[ii] M. Hepperle, Electric Flight – Potential and Limitations, NATO Workshop Energy Efficient Technologies and Concepts of Operation STO-MP-AVT-209, 2012, DOI10.14339/STO-MP-AVT-209, https://elib.dlr.de/78726/1/MP-AVT-209-09.pdf

[iii] Roland Berger GmbH, Report Aircraft Electrical Propulsion – The Next Chapter of Aviation? 2017

[iv] D. Duwe, L. Keicher, P. Ruess, F. Klausmann, Fraunhofer Institute for Industrial Engineering, QUO VADIS 3D MOBILITY -Technological readiness, urban and rural use cases & urban integration of flying cars and passenger drones 2019, http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-5696145.pdf

[v] M. Hirschberg, Stand on the Shoulders of Giants, 2019. http://evtol.news/2019/01/02/stand-on-the-shoulders-of-giants

[vi] M. Hirschberg, Electric VTOL is Taking Off, 2018, http://evtol.news/2018/08/30/electric-vtol-is-taking-off-beware-the-hyper-hype-cycle/

[vii] https://evtol.news/

[viii] https://en.wikipedia.org/wiki/Volocopter_2X

[ix] http://evtol.news/aircraft/ehang

[x] https://evtol.news/aircraft/alauda-airspeeder/

[xi] https://www.electrive.net/2019/10/22/singapur-volocopter-absolviert-ersten-bemannten-flug/

[xii] http://evtol.news/aircraft/kitty-hawk-cora

[xiii] http://evtol.news/aircraft/aurora

[xiv] https://evtol.news/aircraft/lilium/

[xv] https://en.wikipedia.org/wiki/Aurora_XV-24_LightningStrike

[xvi] https://newatlas.com/joby-s2-tilt-rotor-vtol-multirotor-aircraft-concept/40662/

[xvii] https://evtol.news/aircraft/archer/

[xviii] https://evtol.news/aircraft/pop-up-next/

[xix] https://evtol.news/aircraft/autogyro-ecavalon/

[xx] https://www.pal-v.com/

[xxi] https://evtol.news/?s=Terrafugia

[xxii] AUSTRIAN WINGs - Österreichs Luftfahrtmagazin, 27.10.2017

[xxiii] https://en.wikipedia.org/wiki/Eviation_Alice#/media/File:Eviation_Alice.png

[xxiv] https://en.wikipedia.org/wiki/Bye_Aerospace_eFlyer_4

[xxv] https://www.electrive.net/wp-content/uploads/2019/05/bye-aereospace-eflyer2-elektro-flugzeug-electric-aircraft-02.png

[xxvi] https://www.finanznachrichten.de/nachrichten-2019-07/47315820-oxis-energy-to-develop-proof-of-concept-advanced-lightweight-lithium-sulfur-cells-for-bye-aerospace-008.htm

[xxvii] https://en.wikipedia.org/wiki/Gaston_Tissandier

[xxviii] https://en.wikipedia.org/wiki/Hybrid_Air_Vehicles_HAV_304/Airlander_10

[xxix] B. Omar, chapter Experimental studies of using a PEMFC/battery hybrid system to power small UAVs, in Energy and Sustainability V (ed. by, H.H. Al-Kayiem, C.A. Brebbia, S.S. Zubir) WIT Press, 2015, p. 273

[xxx] https://www.hydrogen.energy.gov/pdfs/review18/ia005_stroman_2018_o.pdf

[xxxi] https://www.carscoops.com/2019/05/bmw-designworks-helped-to-create-this-sleek-hydrogen-powered-aircraft/

[xxxii] https://www.ballard.com/docs/default-source/uav/complete-commercial-hydrogen-uav-solution-final.pdf?sfvrsn=f2c1c080_2

[xxxiii] I. Dincer; C. Acar, A review on potential use of hydrogen in aviation applications International Journal of Sustainable Aviation, Vol. 2, No. 1, 2016

[xxxiv] Hydrogen-powered aviation - A fact-based study of hydrogen technology,economics, and climate impact by 2050, https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

[xxxv] https://www.aurora.aero/odysseus-high-altitude-pseudo-satellite-haps/

[xxxvi] https://en.wikipedia.org/wiki/Airbus_E-Fan_X

[xxxvii] M. Keim, J. Kallo, K.A. Friedrich, C. Werner, M. Saballus, F. Gores, Multifunctional fuel cell system in an aircraft environment: An investigation focusing on fuel tank inerting and water generation, Aerospace Science and Technology, 29 (2013) 330-338

[xxxviii] Li-Ionen Battery Roadmap of FhG Institute for System- and Innovation Research (ISI)

[xxxix] Th. Kadyk, Ch. Winnefeld , R. Hanke-Rauschenbach, U. Krewer, Analysis and Design of Fuel Cell Systems for Aviatio, Energies 11 (2018) 375

[xl] G. A. Kerchner, J. Garche, chapter 11 A – Special risks during transport and storage, in Li-Battery Safety, ed. by J. Garche, K. Brandt, Elsevier 2018, pp. 546 – 471

[xli] X. Feng, M. Ouyang and L. Lu, Chapter 12D - Overview About Accidents: Selected Lessons Learned From Prior Safety-Related Failures of Li-Ion Batteries, in Li-Battery Safety, ed. by J. Garche, K. Brandt, Elsevier 2018, pp. 571 - 602

[xlii] Aircraft incident report: auxiliary power unit battery fire, Japan airlines Boeing 787, JA 829J, Boston, Massachusetts, January 7, 2013. National Transportation Safety Board, DC, Rep. No. PB2014-108867, November 21, 2014.

[xliii] N. Goto, Aircraft serious incident investigation report: all Nippon airways Co. Ltd. JA804A. Japan Transport Safety Board, Tokyo, Japan, Report No. AI2014-4, September 25, 2014.

[xliv] B.D. James, 2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles, https://www.energy.gov/sites/prod/files/2018/04/f51/fcto_webinarslides_2018_costs_pem_fc_autos_trucks_042518.pdf

[xlv] B.D. James, C. Houchins, Hydrogen Storage Cost Analysis 2018, https://www.hydrogen.energy.gov/pdfs/review18/st100_james_2018_o.pdf

[xlvi] https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

[xlvii] G. Fredi et al., Graphitic microstructure and performance of carbon fibre Li-ion structural battery electrodes, Multifunctional Materials, 1(2018), Number 1, ttps://doi.org/10.1088/2399-7532/aab707

[xlviii] http://www.airbus.com/company/market/forecast

[xlix] https://www.idtechex.com/en/research-report/manned-electric-aircraft-2020-2030/672

[l] https://www.safran-group.com/media/safran-and-aviations-electric-future-20190613-0

[li] S. DUBOIS, Clean Sky 2 JU, Innovation Takes Off: What kind of aircraft configuration to expect by 2050?, Batterieforum, Berlin (Germany), 23rd January 2020

[lii] https://www.prnewswire.com/news-releases/aircraft-electrification-industry-worth-8-6-billion-by-2030---key-players-are-safran-honeywell-thales-united-technologies-ge-aviation-and-raytheon-301000914.html

[liii] https://www.electrive.com/2020/05/06/exact-dlr-researches-eco-efficient-aircraft/

[liv] https://www.easa.europa.eu/document-library/product-certification-consultations/special-condition-vtol