PROFESSIONAL
EDUCATION

Staircase to Utopia

Advances in Technology Roadmapping and Development

INCOSE New England Chapter | May 18th, 2021

Prof. Olivier de Weck deweck@mit.edu

Prof. Olivier de Weck

1968 Originally from Fribourg, Switzerland

1992 ETH Zurich, Industrial Engineering (major in production and technology management)

1993-1996 McDonnell Douglas, St. Louis, MO

Liaison Engineer and F/A-18 Program Manager

1997-2001 MIT | Aero Astro, S.M. and Ph.D.

2001-present Professor of Aeronautics and Astronautics and Engineering Systems at MIT

2012 INCOSE Fellow

2017-2018 SVP Technology Planning and Roadmapping at Airbus in Toulouse, France

Airbus History

In 2019 Airbus celebrated its 50th Anniversary

Created in 1969 by a Franco-German-UK industrial policy decision not to depend fully on the U.S. for aerospace products

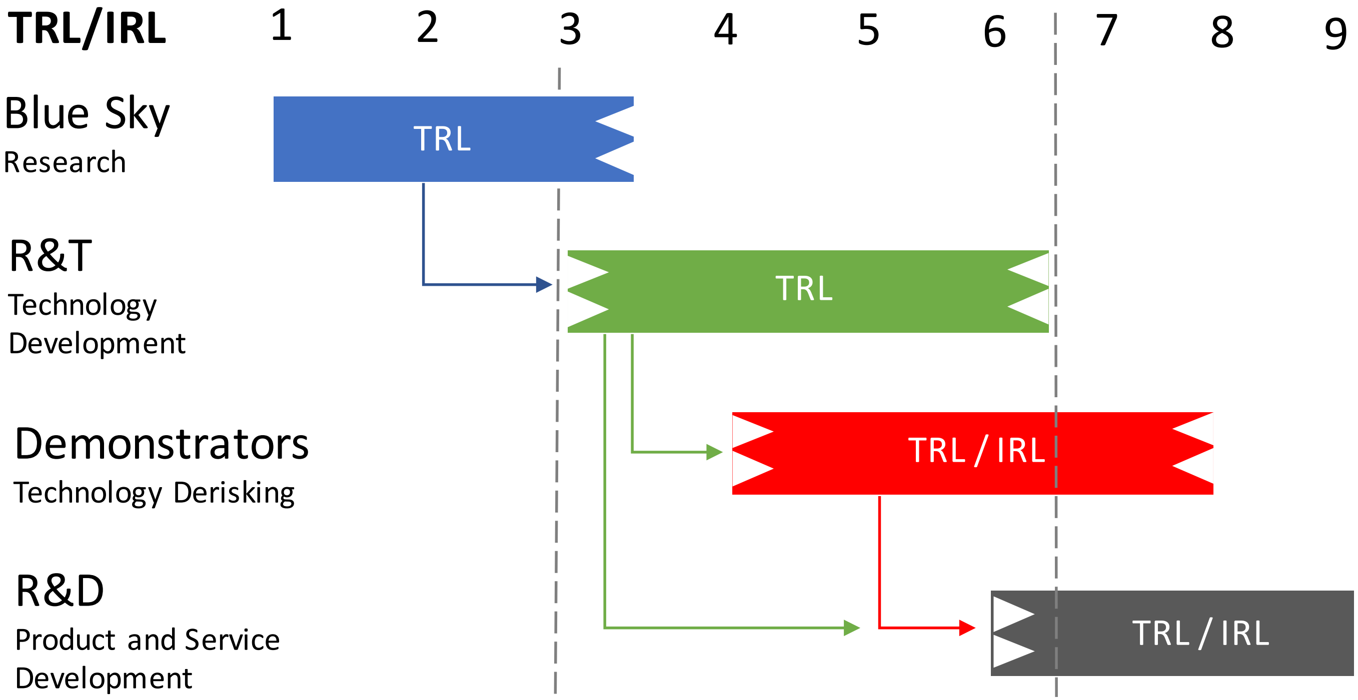
Airbus has absorbed almost all prior national companies under one roof, e.g.

-Sud Aviation - Aerospatiale
-MBB
-Fokker
-Etc …

10 years ago EADS had two co-CEOs, two HQs and country representatives on the board

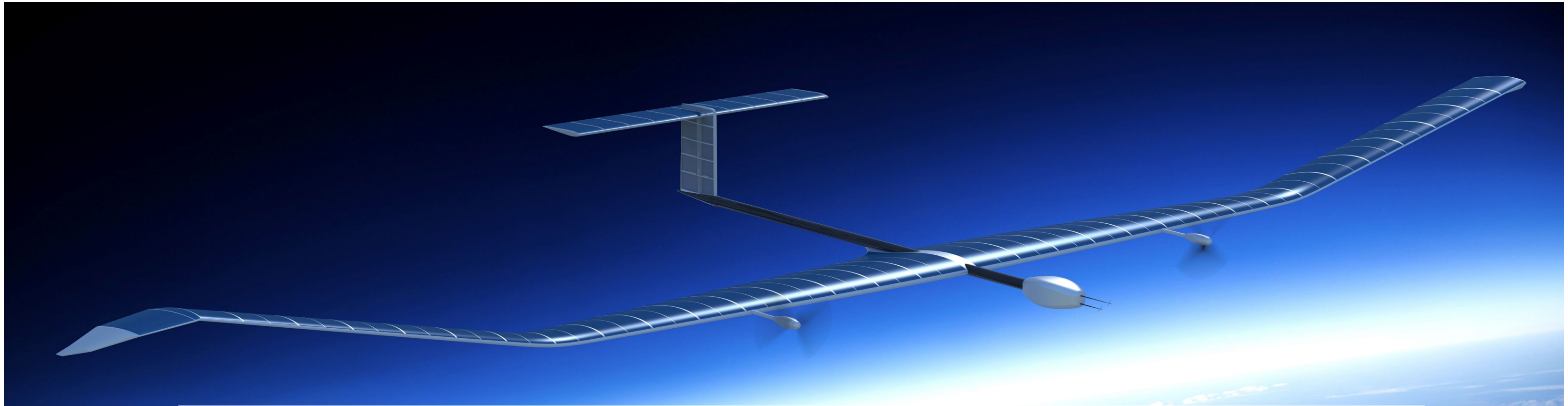
Now **ONE AIRBUS**

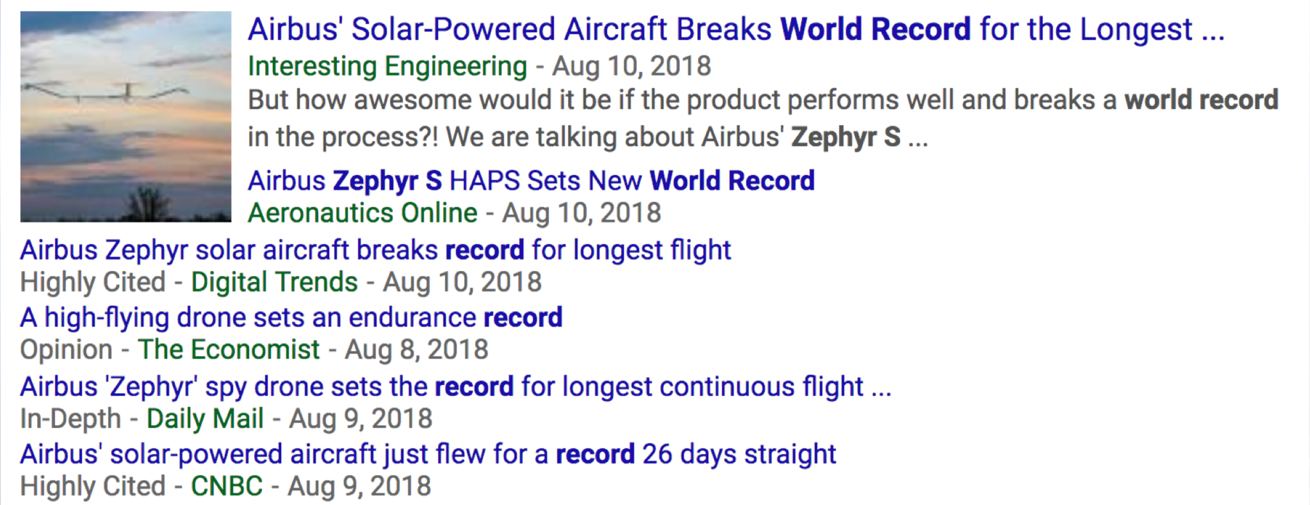
What are the different kinds of R&D investments?



Airbus spends about 3B€ per year on R&D and holds about 40,000 patents worldwide

11 July 2018





Airbus' Solar-Powered Aircraft Breaks **World Record** for the Longest ...
Interesting Engineering - Aug 10, 2018
But how awesome would it be if the product performs well and breaks a **world record** in the process?! We are talking about Airbus' **Zephyr S** ...

Airbus **Zephyr S** HAPS Sets New **World Record**
Aeronautics Online - Aug 10, 2018

Airbus Zephyr solar aircraft breaks **record** for longest flight
Highly Cited - Digital Trends - Aug 10, 2018

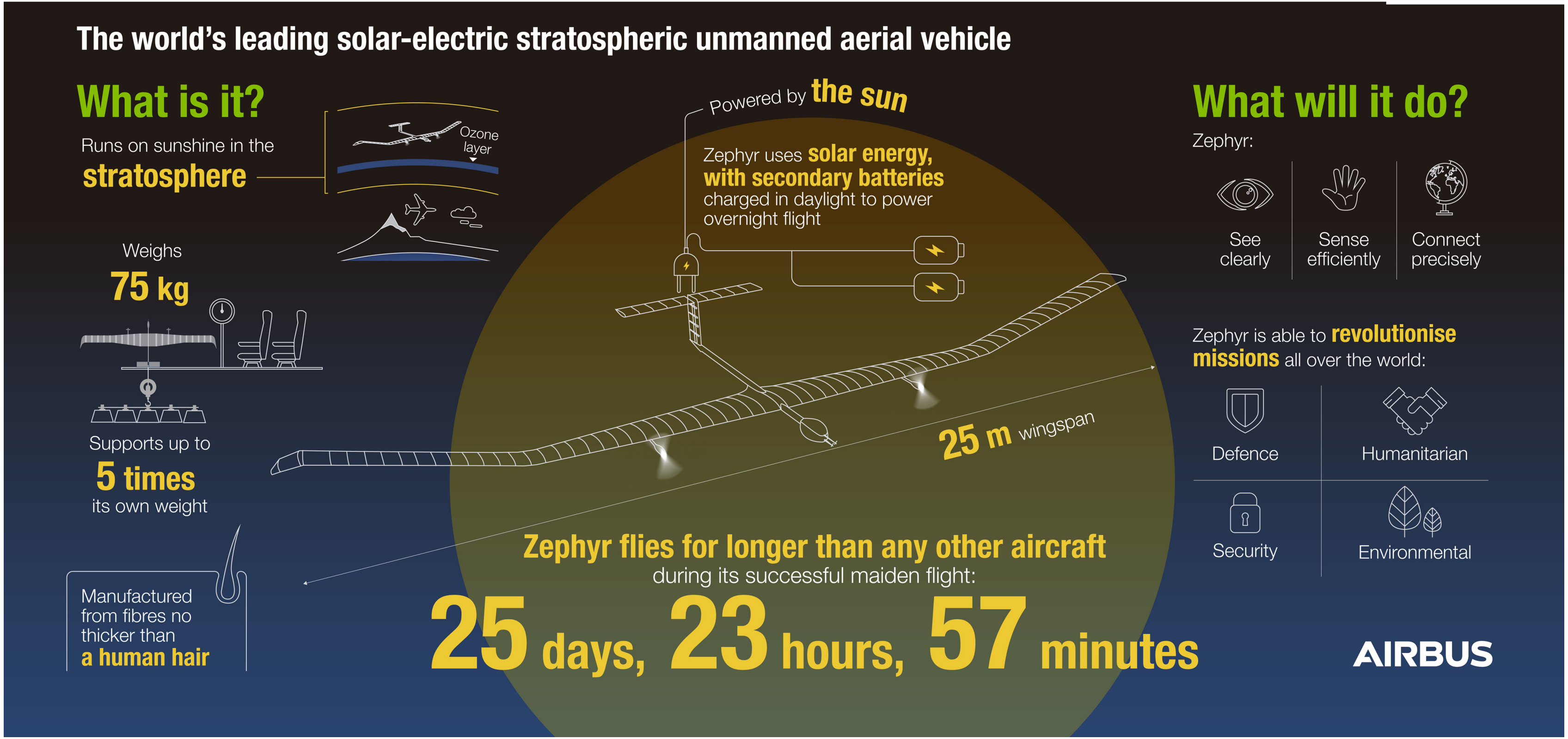
A high-flying drone sets an endurance **record**
Opinion - The Economist - Aug 8, 2018

Airbus 'Zephyr' spy drone sets the **record** for longest continuous flight ...
In-Depth - Daily Mail - Aug 9, 2018

Airbus' solar-powered aircraft just flew for a **record** 26 days straight
Highly Cited - CNBC - Aug 9, 2018

Zephyr

Pioneering the stratosphere



The world's leading solar-electric stratospheric unmanned aerial vehicle

What is it?

Runs on sunshine in the **stratosphere**

Weighs **75 kg**

Supports up to **5 times** its own weight

Manufactured from fibres no thicker than **a human hair**

Powered by **the sun**

Zephyr uses **solar energy, with secondary batteries** charged in daylight to power overnight flight

25 m wingspan

Zephyr flies for longer than any other aircraft
during its successful maiden flight:

25 days, 23 hours, 57 minutes

What will it do?

Zephyr:

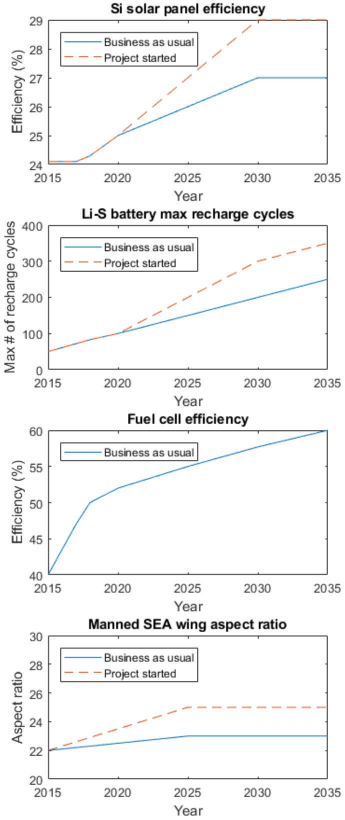
- See clearly
- Sense efficiently
- Connect precisely

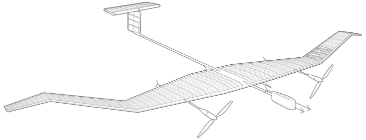
Zephyr is able to **revolutionise missions** all over the world:

- Defence
- Humanitarian
- Security
- Environmental

AIRBUS

Which technologies should we invest in to fly longer and carry more payload?

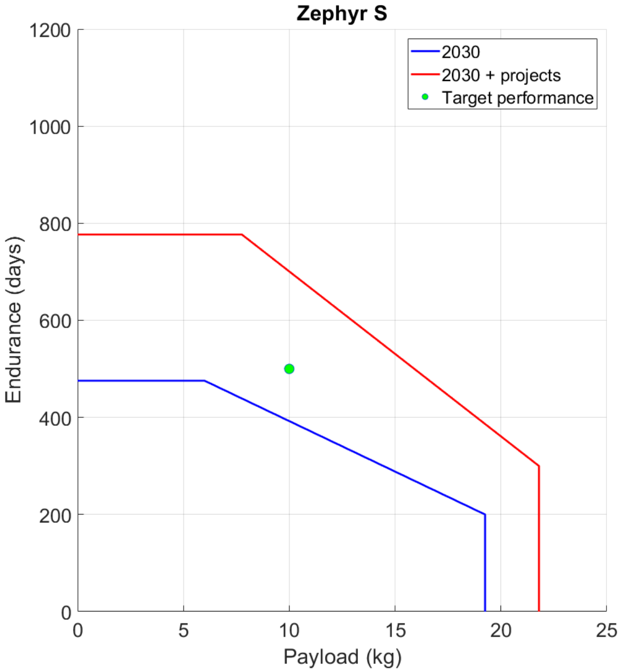




Product-specific technical model (i.e. *transfer function*)

$$Product\ FOMs = (y_1, y_2, \ldots, y_m)$$
$$Technology\ FOMs = (x_1, x_2, \ldots, x_n)$$

$$(y_1, y_2, \ldots, y_m) = f(x_1, x_2, \ldots, x_n)$$



Choosing the right R&T projects

Scenario #1 – no projects

Target requirement: HAPS (i.e. Zephyr) with 10 kg of p

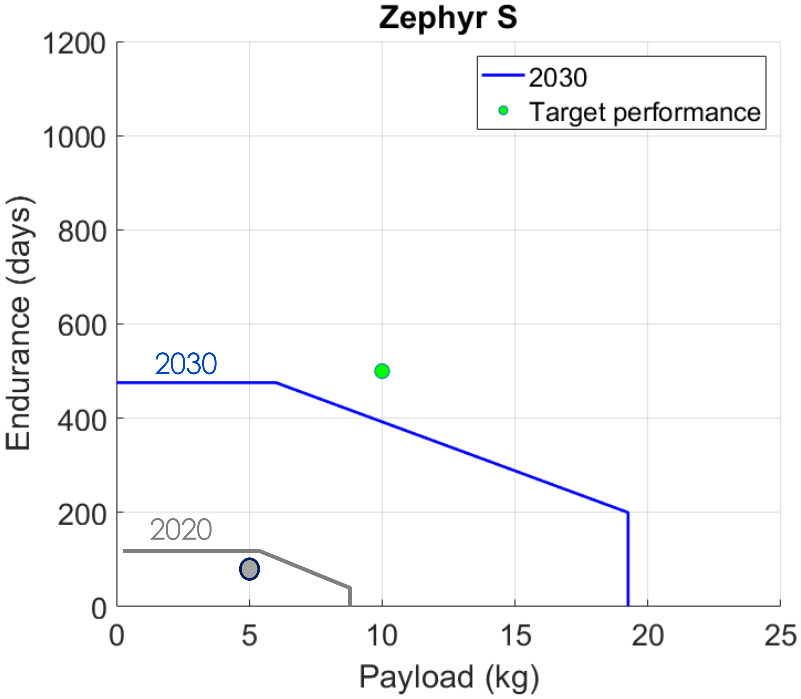
R&T projects available:

1)Li-S battery improvements,

2)Solar cell improvements,

3)Structural improvements

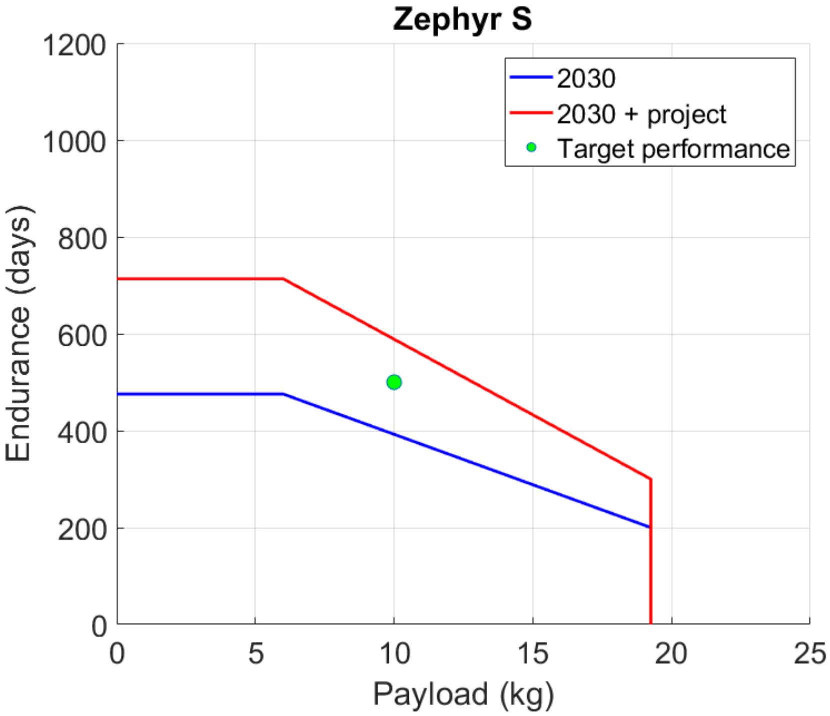
Unable to meet target by 2030 with no projects.



Choosing the right R&T projects

Scenario #4 – start project: Li-S battery improvements

Able to meet target by 2030 with Li-S battery improve

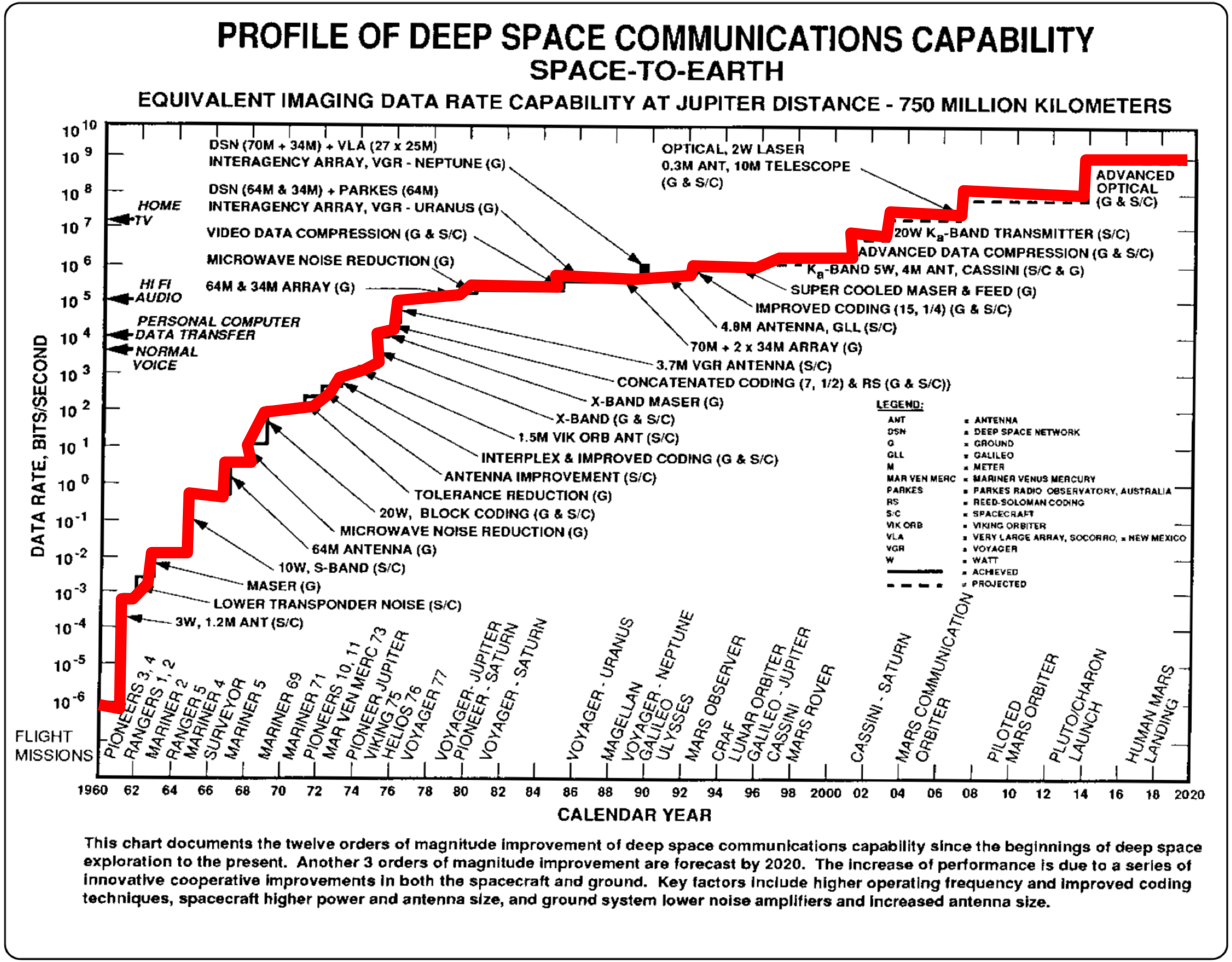


Technological Progress

How do we quantify and explain it?

Jet Propulsion Laboratory
California Institute of Technology

Deep Space Network (DSN)

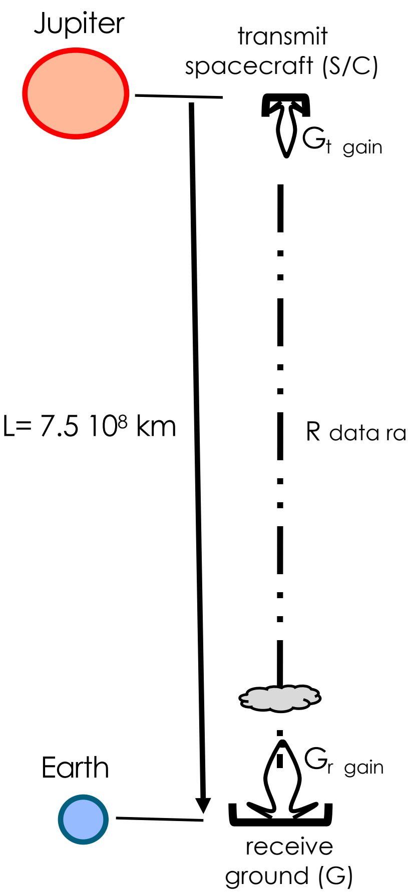


PROFILE OF DEEP SPACE COMMUNICATIONS CAPABILITY

SPACE-TO-EARTH

EQUIVALENT IMAGING DATA RATE CAPABILITY AT JUPITER DISTANCE - 750 MILLION KILOMETERS

This chart documents the twelve orders of magnitude improvement of deep space communications capability since the beginnings of deep space exploration to the present. Another 3 orders of magnitude improvement are forecast by 2020. The increase of performance is due to a series of innovative cooperative improvements in both the spacecraft and ground. Key factors include higher operating frequency and improved coding techniques, spacecraft higher power and antenna size, and ground system lower noise amplifiers and increased antenna size.



Jupiter

transmit spacecraft (S/C)

G_t gain

L= 7.5 10^8 km

R data rate

Earth

G_r gain

receive ground (G)

Link Budget Equation [logarithmic dB version]

Data Rate

Shannon's Limit

Space Loss

Boltzmann Constant

$$R = EIRP - \frac{Eb}{No} + L_s + L_a + G_r - T_s - k - M$$

Effective Isotropic Radiated Power (S/C)

Block Coding (1970)
Data Compression (1985)

Transmission Path Loss

Receiver Antenna Gain

System Temperature

Link Margin

$$EIRP = G_t + P + L_l$$

Transmit Power
3W (1962)
10W (1966)
20W (1970)

$$D_t = 10^{\left(\frac{G_t - 17.8 - 20\log(f)}{20}\right)}$$

G Antenna
34m (1962)
64m (1988)
70m (1992)

Receiver
Lower Noise (1962)
Cooling System (1998)

S/C Antenna Diameter
1.2m (1962)
4.8m (1992)
10m (2020+)

Frequency
S-Band (1966)
X-Band (1978)
Ka-Band (2000)
Optical (2020+)

Enabling Technologies (Antennas, Transmitters, Coolers, Waveforms)

A350-900 ULR EIS **11 October 2018**

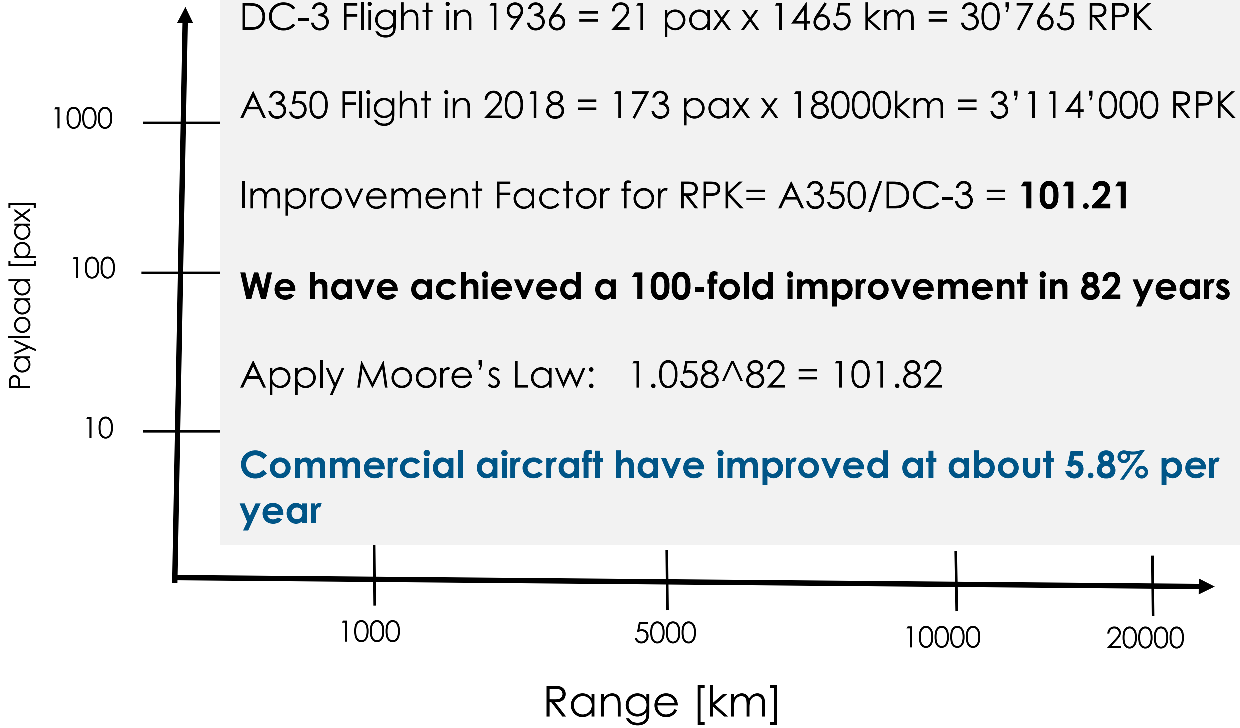
DC-3 First Flight 17 December 1935

Let's compare the specifications of the two aircraft…

	DC-3A	A350-900 ULR
Entry-in-Service [EIS year]	1936	2018
Gross Takeoff Weight [kg]	11’430	280’000
Payload [kg]**	2’700	53’300
Passengers [pax]	21	173
Max Range* [km]	1’465	18’000
Wingspan [m]	29	64.75
Finesse [cruise L/D]	14.7	>19
Cruise Speed [km/h]	333	903
Specific Fuel Consumption* [mg/sN]	18	<15
Engines	Wright R-1820 Cyclone 9s	Rolls Royce Trent XWB-84

estimates* * max payload excluding fuel*

Aviation’s progress over the last 80+ years is also impressive



DC-3 Flight in 1936 = 21 pax x 1465 km = 30’765 RPK

A350 Flight in 2018 = 173 pax x 18000km = 3’114’000 RPK

Improvement Factor for RPK= A350/DC-3 = **101.21**

We have achieved a 100-fold improvement in 82 years !

Apply Moore’s Law: 1.058^82 = 101.82

Commercial aircraft have improved at about 5.8% per year

Figures of Merit (FOMs)

Range

Payload

Safety

Operational Reliability

Cash Operating Cost

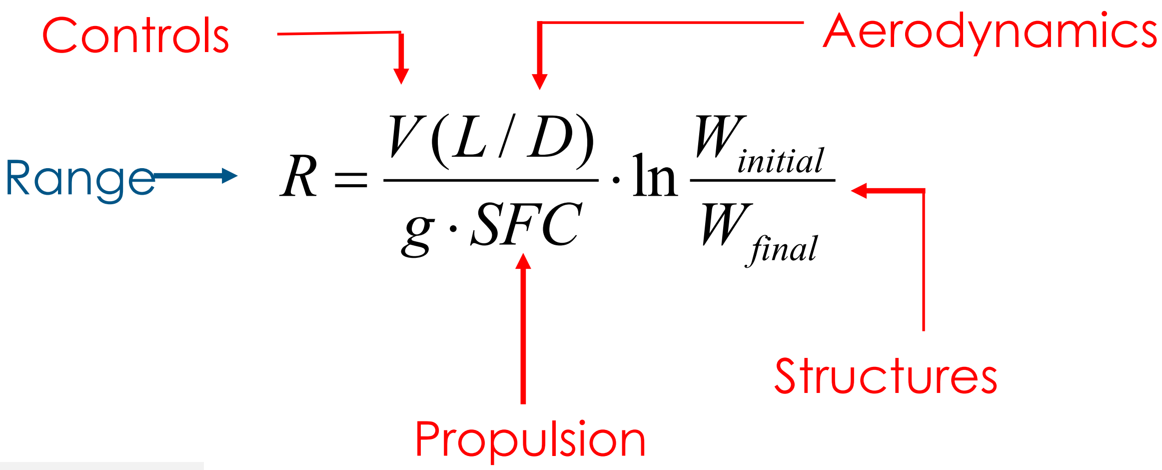
Aircraft Price

Emissions

RPK = revenue-pax-kilometer

What is the Bréguet Range Equation telling us?

Louis Charles Breguet pilotant son premier aéroplane (Breguet I) en juin 1909 à La Brayelle près de Douai. (Musée de l'Air).



Controls

Aerodynamics

Range

$$R = \frac{V(L/D)}{g \cdot SFC} \cdot \ln \frac{W_{initial}}{W_{final}}$$

Structures

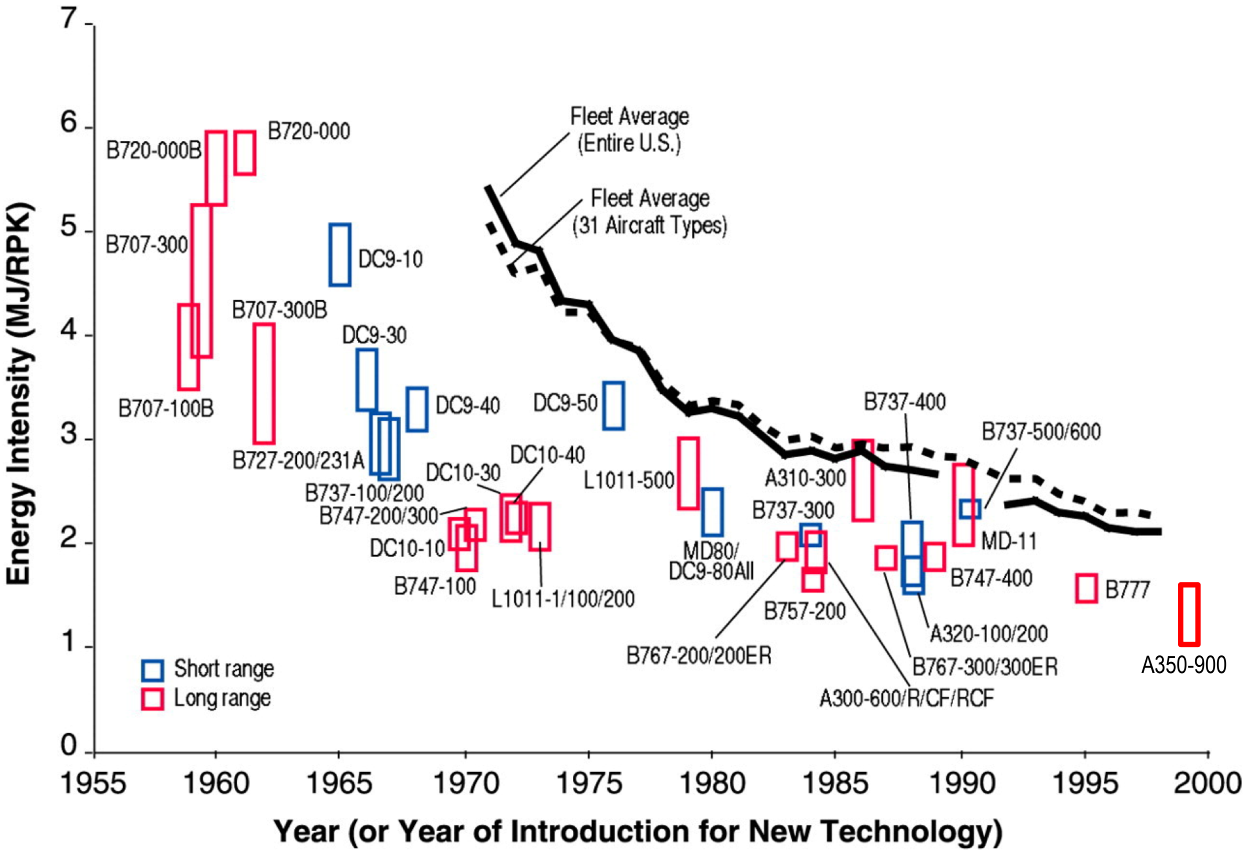
Propulsion

R = Range [m]
V = Flight velocity [m/s]
SFC = Specific Fuel Consumption [kg/s/N]
L/D = Lift-over-Drag ratio (Finesse) [-]
g = gravitational acceleration [m/s^2]
$W_{initial}$ = Initial (takeoff) weight [N]
W_{final} = Weight at end of flight [N]
$W_{fuel}=W_{initial}-W_{final}$ Fuel quantity [N]

Concurrently improving aircraft configurations, technologies and flight operations has achieved the "miracle" of modern aviation.

Which technology contributes what?

Historical improvement in Energy Intensity of Aviation



Big emphasis on burning less fuel per revenue pax km (RPK)

Delay between introduction of new technology and effect on fleet average: 10-15 years

Average annual rate of improvement since 1950s has been 3.3% per year

Key Contributor: Better Engines

If engines contributed 3.3% per year, the other technologies together are responsible for about 2.5% per year in terms of ΔRPK/Δt

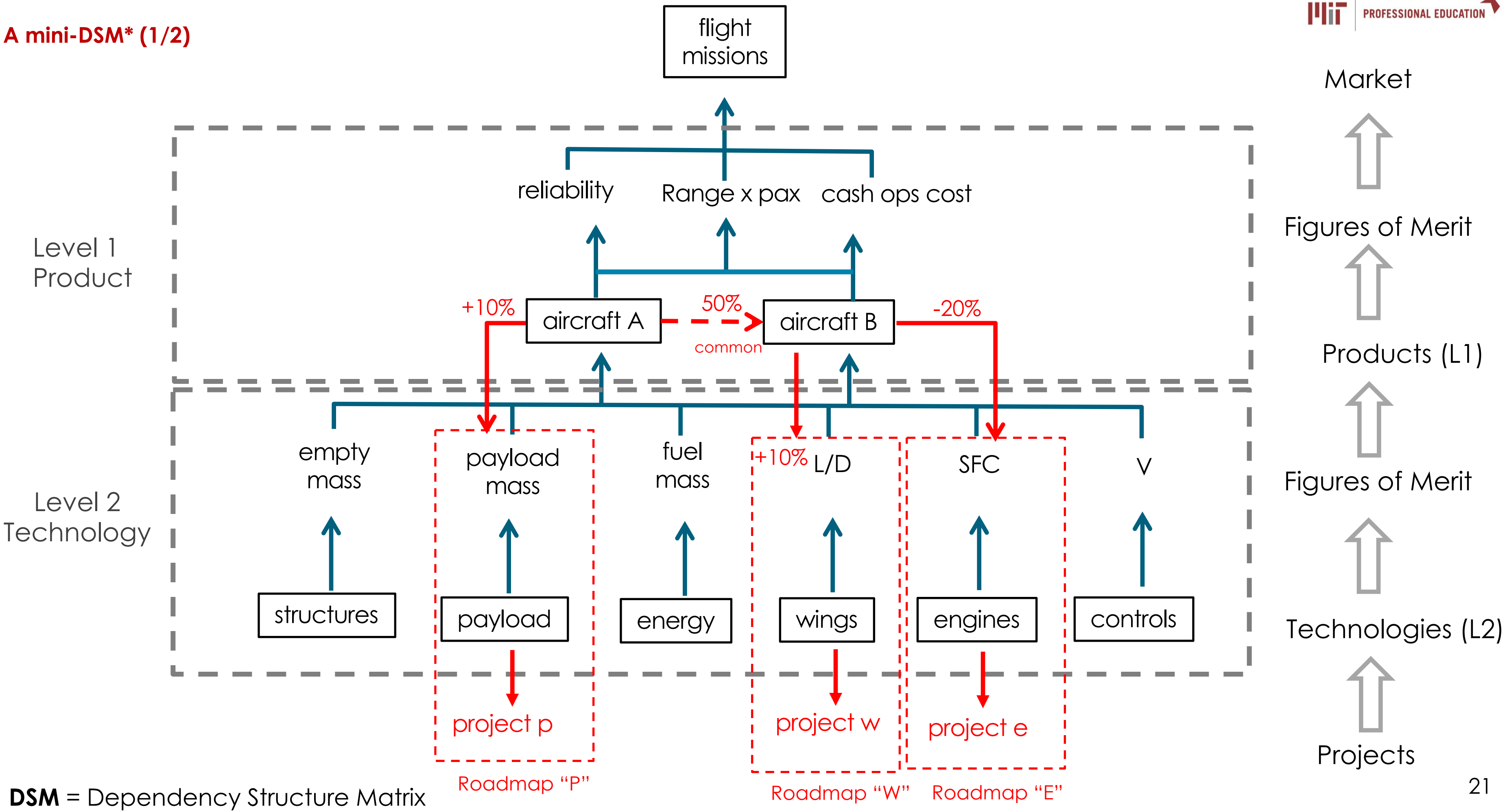
Source: Lee, J.J., Lukachko, S.P., Waitz, I.A. and Schafer, A., 2001. Historical and future trends in aircraft performance, cost, and emissions. *Annual Review of Energy and the Environment*, *26*(1), pp.167-200.

Some Terminology …

Term	DSN Example
Level 1 System	Deep Space Network
Level 2 Technology "Bricks"	Spacecraft Antenna, Ground Antenna, Transmitter, Decoder etc…
Figure of Merit at L1	Data Rate R [bits/sec]
Figure of Merit at L2	Gain, Power [W], Antenna Size [m], Frequency [Hz], Temperature [K]
Transfer Function	Link Budget Equation
Rate of Progress (CARP)*	77.8% per year (!)
FOM Chain	R = f(EIRP = f(Gt = f (Dt, f)))

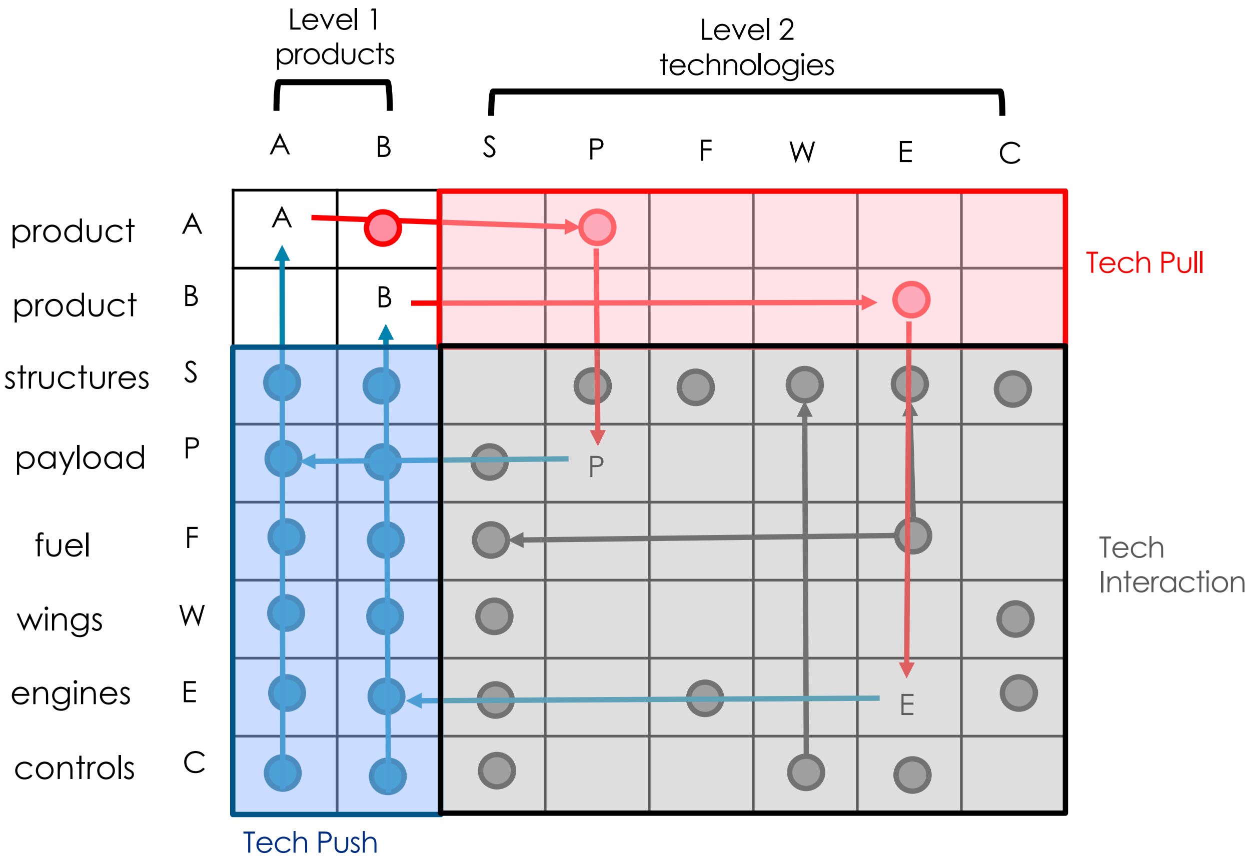
*Compound Annual Rate of Progress

A mini-DSM* (1/2)



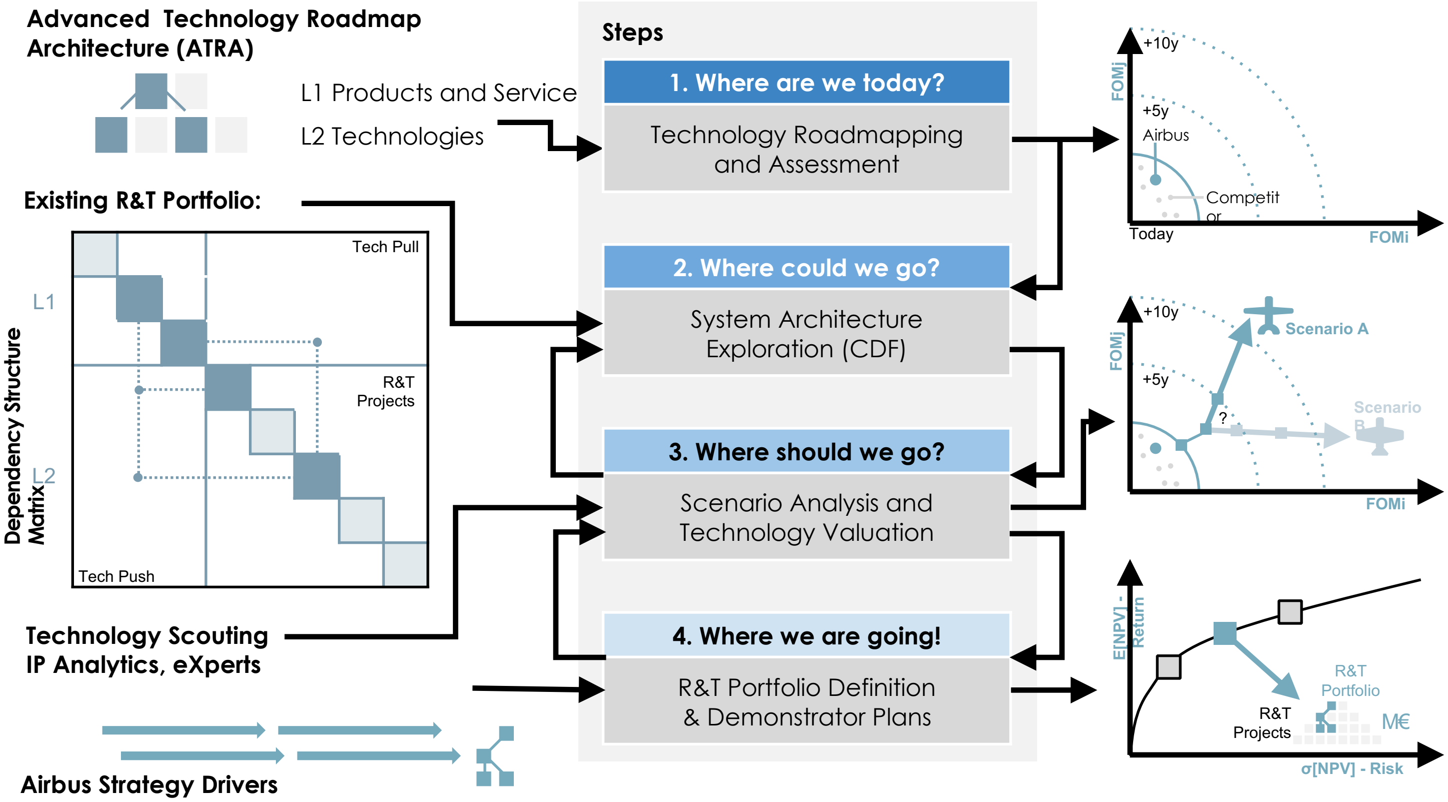
DSM = Dependency Structure Matrix

A mini-DSM (2/2)



Technology roadmap <u>must</u> contain at a minimum : technology scope, link to product(s)/service(s), FOMs trends and targets, projects

Advanced Technology Roadmapping Methodology



Inputs

Advanced Technology Roadmap Architecture (ATRA)

L1 Products and Service

L2 Technologies

Existing R&T Portfolio:

Technology Scouting
IP Analytics, eXperts

Airbus Strategy Drivers

Steps

1. Where are we today?
Technology Roadmapping and Assessment

2. Where could we go?
System Architecture Exploration (CDF)

3. Where should we go?
Scenario Analysis and Technology Valuation

4. Where we are going!
R&T Portfolio Definition & Demonstrator Plans

Outputs

Technology Roadmaps (L2)

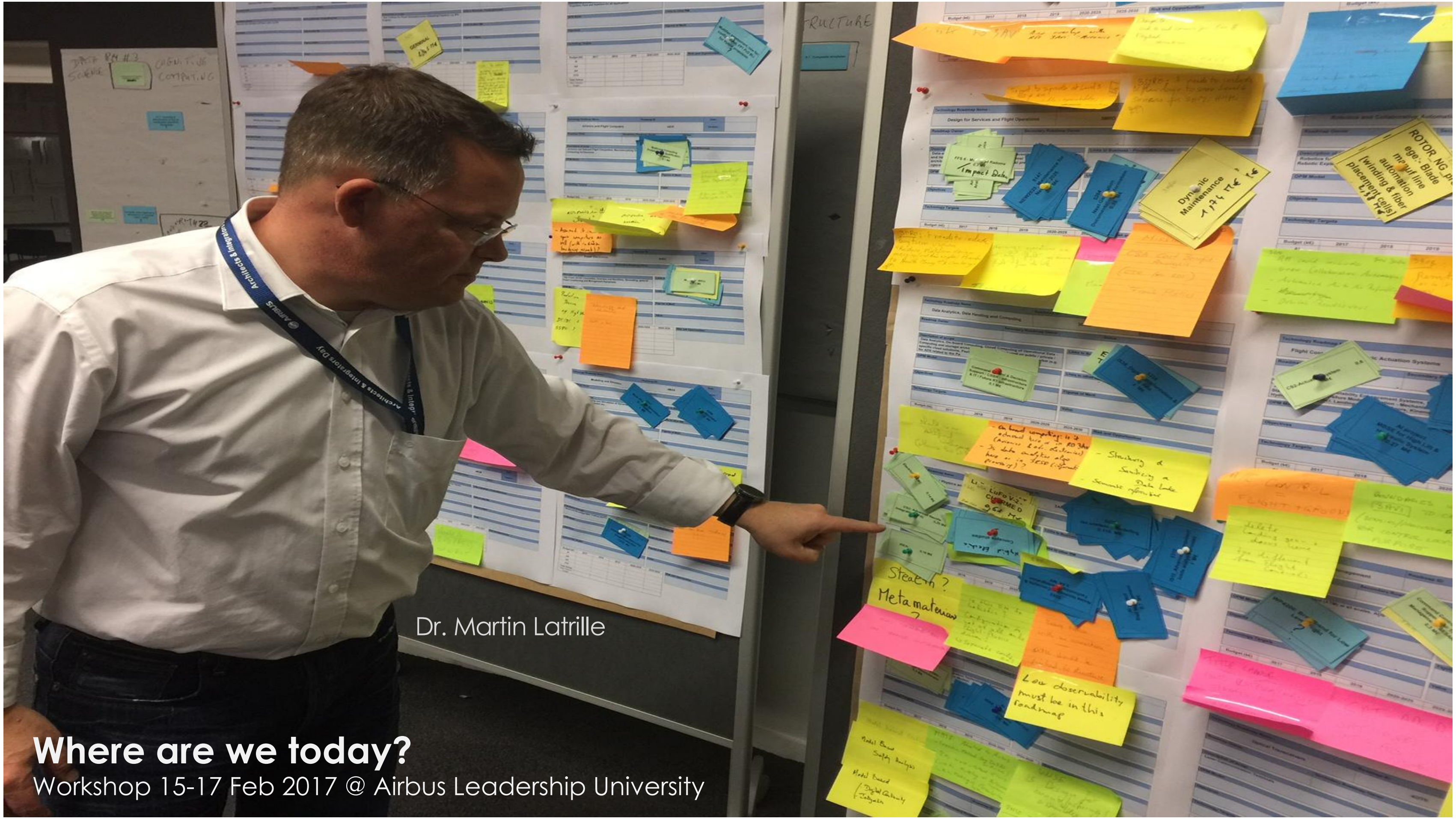
Figures of Merit (FOM)
Current Best-In Class
Tech Trends dFOM/dt
Techno Readiness Levels (TRL)
Roadmap Maturity Score

Scenarios (L1)

Reference Products and Services
Project Value Propositions
Technology Valuation
Investment Scenarios
Vector Charts

R&T Portfolio

Proposed R&T Portfolio
Integrated OP Budget for R&T (incl. CTO and Divisions)
Synergy Projects
Demonstrators Plan
(Expected ΔNPV and Risk)



Dr. Martin Latrille

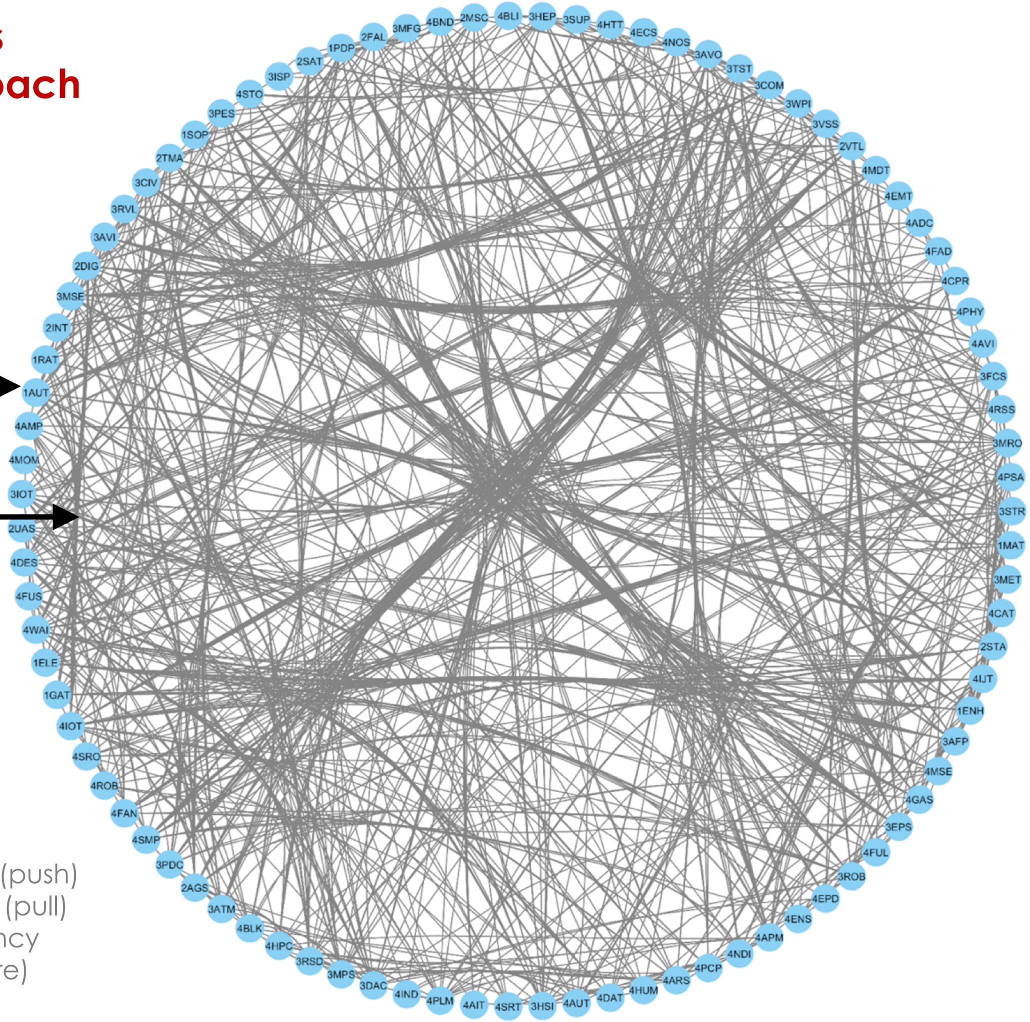
Where are we today?

Workshop 15-17 Feb 2017 @ Airbus Leadership University

ARCHITECTURE: **Valode & Pistre**

Airbus Leadership University

Technology interdependencies identified using the ATRA approach



Technology Roadmaps

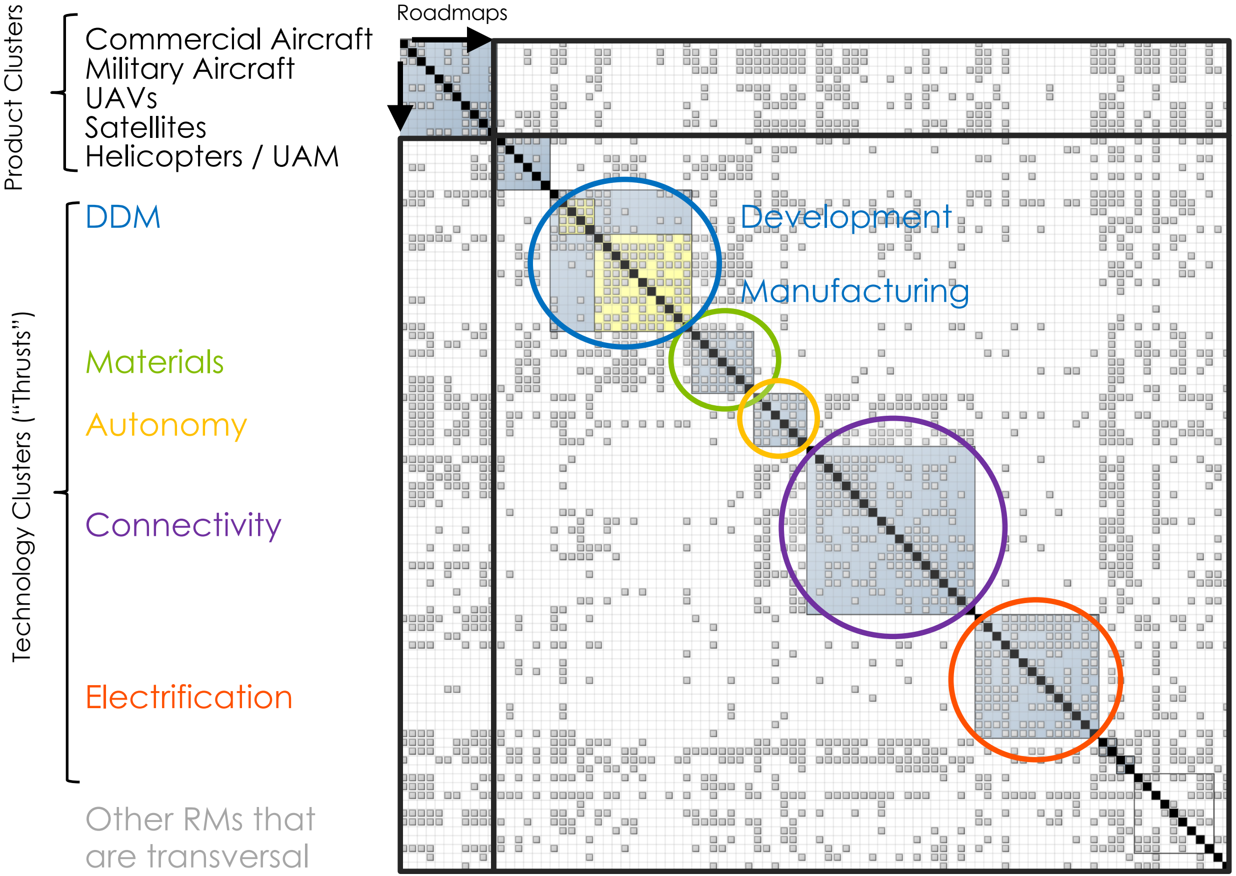
Interdependencies

Over 3,000 interdependencies found

A technology roadmap interdependency indicates that two RM are directly linked via:

-Delivery of technology from one to another (push)
-Requirements imposed from one to another (pull)
-Quantified links through FOM interdependency
-Shared projects (up to 3 roadmaps can share)

Technology Roadmap Clustering (DSM 2017)



Dependency Structure Matrix (DSM) reveals grouping of roadmaps into tightly coupled clusters of technologies

All links shown here have been mutually agreed pairwise by roadmap owners (RMOs)

We used DSM to detect conflicts between technology "push" and "pull" and acknowledged technology interactions

We resolved conflicts during "speed-dating at technology roadmap "camps". Some conflicts remain

DSM created with CAM software

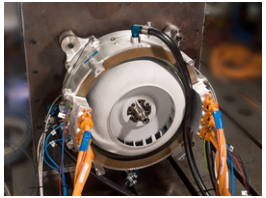
Where could we go?

Martian Drone CDF Session with ADS – August 2017

Sample of Technologies in R&D Portfolio

Electrification

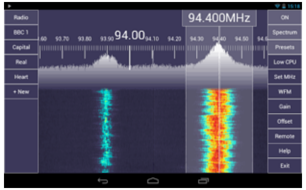
2MW-class Hybrid-Electric Propulsion



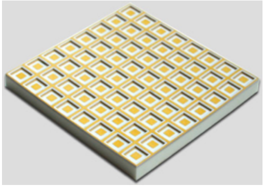
Fault-Tolerant Electric VTOL

Connectivity

Software Defined Radio

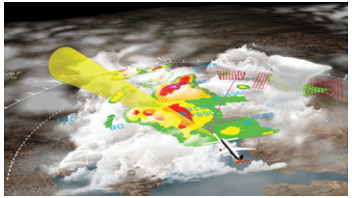


Conformal Antenna Arrays



Autonomy

Adaptive Mission Planning Systems

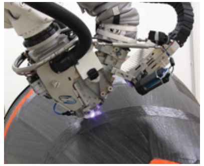


Single Pilot Operations

Materials

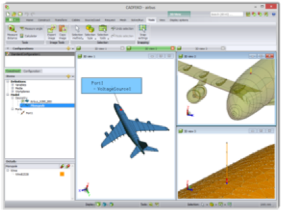
Additive 3D Manufacturing with Metals

Dry-Fiber (Out-of-Autoclave) Composites

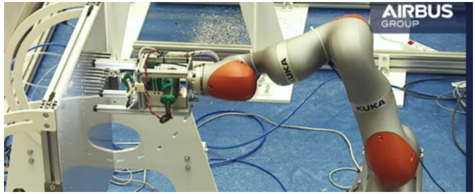


Digital Design and Manufacturing (DDM)

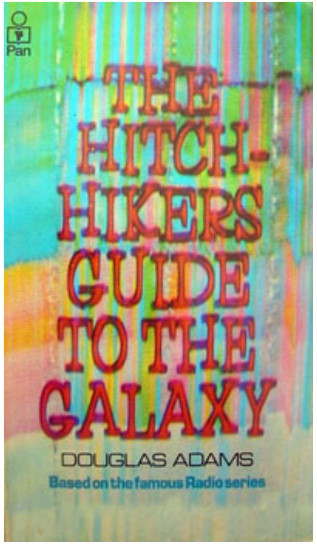
Model-Based Systems Engineering

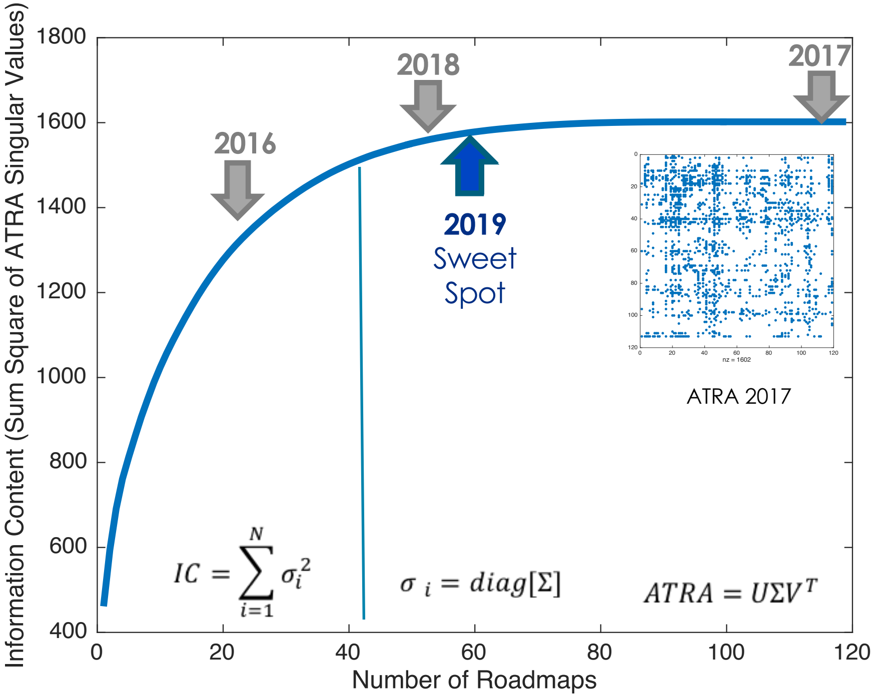


Collaborative and Reconfigurable Robotics



What is the right number of technology roadmaps ? (SVD of DSM)





The R&D Matrix with L1 and L2 remains close to the “sweet spot” of information content

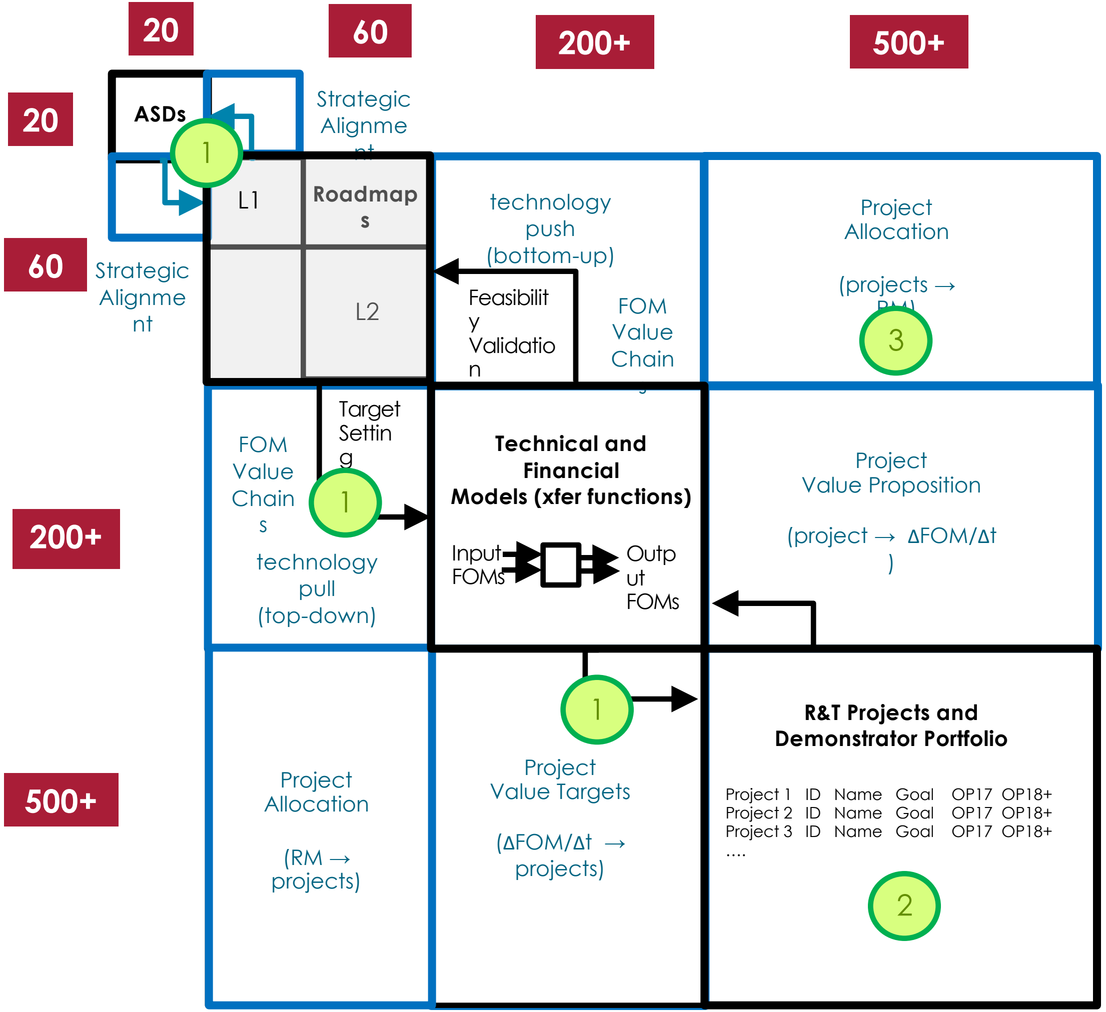
Advanced Technology Roadmapping Architecture (ATRA) as a system

Advanced Strategic Drivers (ASD) for R&D

ATRA Technology Roadmaps

Figures of Merit (FOM)

R&T Projects Portfolio



Reasons for ATRA
1 – Strategic Alignment
2 – Create Synergies
3 – Avoid Blind Spots

Application of ATRA to NASA Space Technology Portfolio (2021-2024)

Latest

NASA Analysis: Earth Is Safe From Asteroid Apophis for 100-Plus Years
2 days ago

NASA Provides $45M Boost to US Small Businesses
3 days ago

Hubble Spots a Galaxy with a Peculiar Arm
3 days ago

Direct Observations Confirm that Humans are Throwing Earth's Energy Budget off Balance
3 days ago

Data Turned Into Sounds of Stars, Galaxies, Black Holes
4 days ago

Major Earth Satellite to Track Disasters, Effects of Climate Change
4 days ago

Jan 7, 2021

Advanced Space Technology Roadmapping Architecture (ASTRA)

Olivier de Weck
Massachusetts Institute of Technology

ESI20 de Weck Quadchart

The Advanced Space Technology Roadmapping Architecture (ASTRA) project will develop and deploy a state-of-the-art methodology for space technology valuation and technology portfolio construction using both integrated modeling and simulation and rigorous Markowitz portfolio theory. ASTRA builds on the Commercial Space Technology Roadmaps (2016-2018) and will organically integrate with the new NASA technology taxonomy (TX01-TX17), the mission-driven NASA technology roadmaps as well as the TechPort database . The ASTRA methodology consists of four steps, each with its own guiding question: (1) Where are we today ?, (2) Where could we go ? (3) Where should we go?, and (4) Where are we really going? This culminates in Technology Investment Portfolio Valuation, Optimization and Selection. ASTRA enables prioritization of mission-specific and general technology investments in a rational way. This includes the identification of optimal timing and opportunities for synergy. ASTRA will be demonstrated and applied to the entire NASA technology portfolio over a period of 3 years using 5 case studies: Artemis, Mars Sample Return (MSR), Nancy Grace Roman Space Telescope (formerly WFIRST), Earth Observation and Cross-Cutting Technologies. ASTRA will also support the annual NASA technology budgeting and prioritization process.

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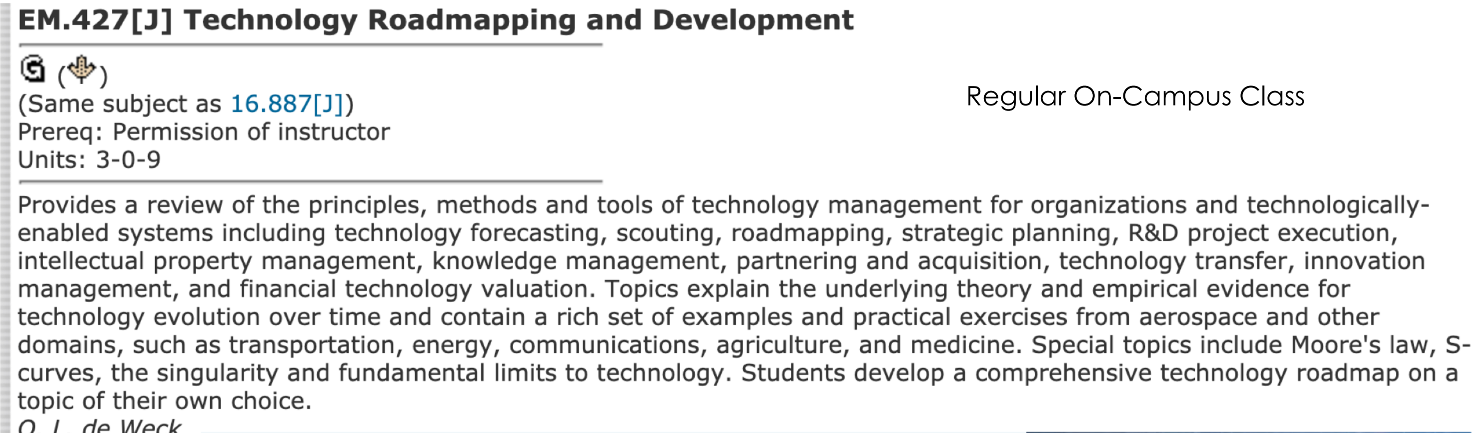
Last Updated: Jan 12, 2021
Editor: Loura Hall

https://www.nasa.gov/directorates/spacetech/strg/early-stage-innovations-esi/esi2020/astra/

Technology Roadmapping @MIT

http://roadmaps.mit.edu



EM.427[J] Technology Roadmapping and Development

(Same subject as 16.887[J])
Prereq: Permission of instructor
Units: 3-0-9

Provides a review of the principles, methods and tools of technology management for organizations and technologically-enabled systems including technology forecasting, scouting, roadmapping, strategic planning, R&D project execution, intellectual property management, knowledge management, partnering and acquisition, technology transfer, innovation management, and financial technology valuation. Topics explain the underlying theory and empirical evidence for technology evolution over time and contain a rich set of examples and practical exercises from aerospace and other domains, such as transportation, energy, communications, agriculture, and medicine. Special topics include Moore's law, S-curves, the singularity and fundamental limits to technology. Students develop a comprehensive technology roadmap on a topic of their own choice.

O. L. de Weck

Regular On-Campus Class

Professional Education Class at MIT PE online

Management of Technology: Roadmapping & Development

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Lead Instructor(s)
Olivier de Weck

Date(s)
Apr 20 - Jun 22, 2021

Location
Online

Course Length
9 weeks

https://professional.mit.edu/course-catalog/management-technology-roadmapping-development

Management of Technology

Strategy & Portfolio Analysis

This program is **designed to expand upon the knowledge acquired by professionals in Management of Technology: Roadmapping & Development.**

What's next?

You will explore how to build and manage an efficient technology portfolio, examining how to thoroughly analyze it while also uncovering what we can expect from technology in the future. To do so, you will be provided with a rich set of examples and practical exercises from diverse industries.

Start

June 22nd, 2021

Duration

9 weeks

Commitment

8-10 hours a week

Format

Online

Be the first to learn everything about the program:

Questions? Comments?