Future aircraft concepts and Artifical Intelligence in aeronautics

By Xavier Dutertre

Learning is changing®

Training Agenda – 4 Days

- **Day 1**
  - **Introduction to future aircraft concepts and Artifical Intelligence in aeronautics**
- Day 2
  - Innovative aircraft concepts
- Day 3
  - MBSE (Model-based systems engineering)
- Day 4
  - Composites, advanced test technologies, aerodynamic shape optimization and multidiciplinary optimization methods

Day 1 – New aircraft concepts and AI in ero

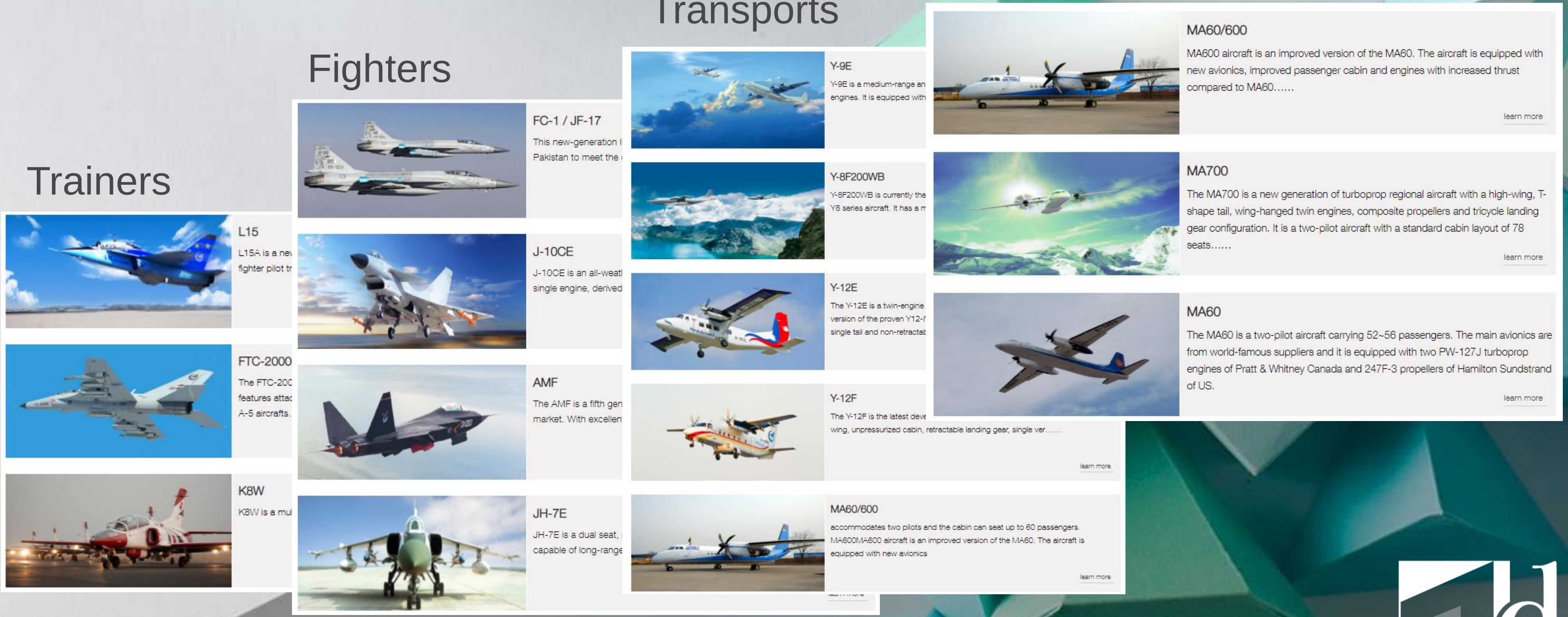
Introduction : New aircraft concepts

- Brief historical review of aircraft shapes
- Aircraft’s design spaces
- Presentation of new types of aircrafts

Artificial Intelligence in aeronautics

- Definition and state of the art of AI in aeronautics
- Applications of IA in aeronautics
- Example of AI applications
  - Aircraft design
  - Flight path optimization
  - Industrial supply chain performance

AVIC aircrafts



Commercial aircrafts

MA60/600

MA600 aircraft is an improved version of the MA60. The aircraft is equipped with new avionics, improved passenger cabin and engines with increased thrust compared to MA60……

learn more

MA700

The MA700 is a new generation of turboprop regional aircraft with a high-wing, T-shape tail, wing-hanged twin engines, composite propellers and tricycle landing gear configuration. It is a two-pilot aircraft with a standard cabin layout of 78 seats……

learn more

MA60

The MA60 is a two-pilot aircraft carrying 52~56 passengers. The main avionics are from world-famous suppliers and it is equipped with two PW-127J turboprop engines of Pratt & Whitney Canada and 247F-3 propellers of Hamilton Sundstrand of US.

learn more

Transports

Y-9E

Y-9E is a medium-range an

engines. It is equipped with

Y-8F200WB

Y-8F200WB is currently the

Y8 series aircraft. It has a m

Y-12E

The Y-12E is a twin-engine

version of the proven Y12-I

single tail and non-retractab

Y-12F

The Y-12F is the latest deve

wing, unpressurized cabin, retractable landing gear, single ver……

learn more

MA60/600

accommodates two pilots and the cabin can seat up to 60 passengers. MA600MA600 aircraft is an improved version of the MA60. The aircraft is equipped with new avionics

learn more

Fighters

FC-1 / JF-17

This new-generation l

Pakistan to meet the

J-10CE

J-10CE is an all-weat

single engine, derived

AMF

The AMF is a fifth gen

market. With excellen

JH-7E

JH-7E is a dual seat,

capable of long-range

Trainers

L15

L15A is a new

fighter pilot tr

FTC-2000

The FTC-200

features attac

A-5 aircrafts.

K8W

K8W is a mul

demos

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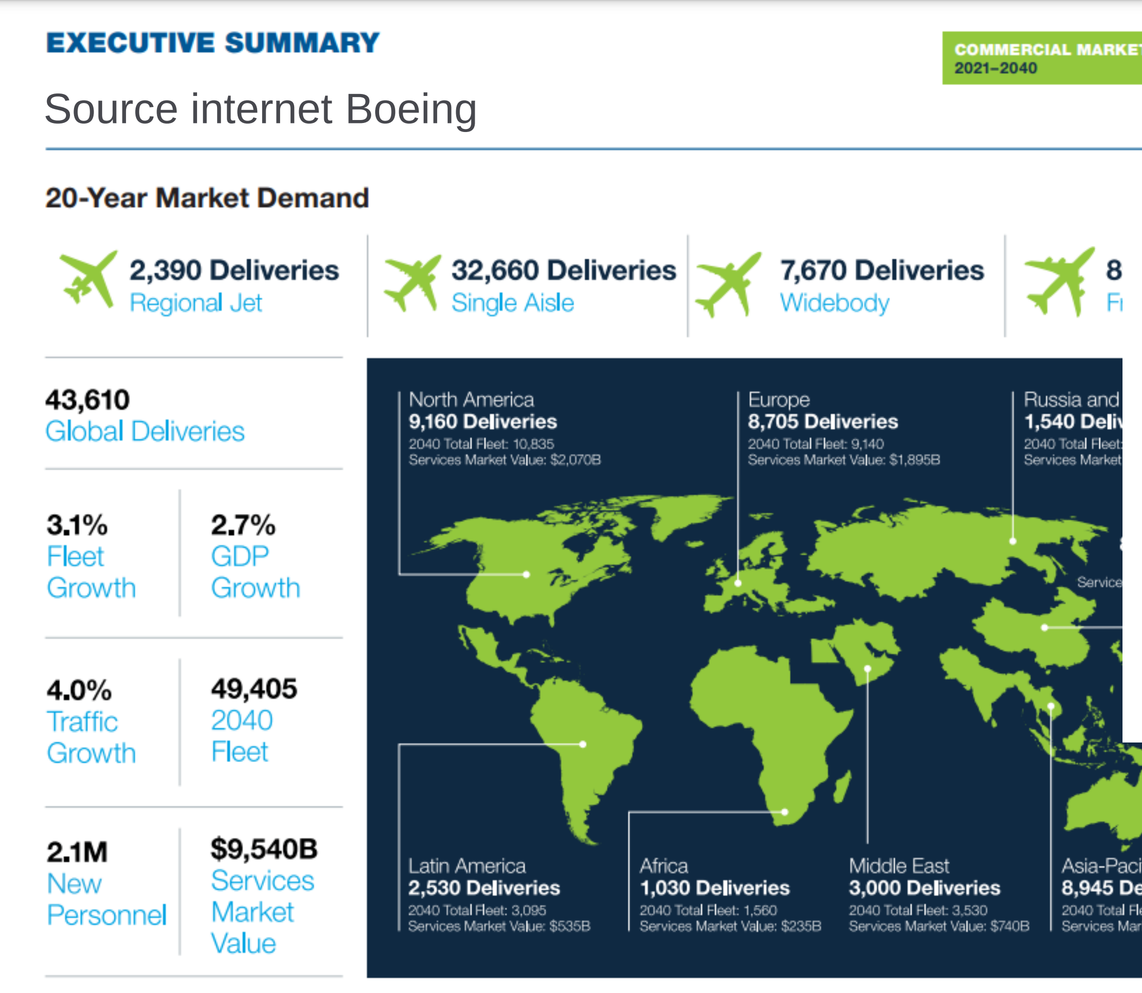
Commercial aircrafts - Example of market studies



EXECUTIVE SUMMARY

COMMERCIAL MARKET OUTLOOK
2021–2040

Source internet Boeing

20-Year Market Demand

2,390 Deliveries
Regional Jet

32,660 Deliveries
Single Aisle

7,670 Deliveries
Widebody

8
F

43,610
Global Deliveries

3.1%
Fleet Growth

2.7%
GDP Growth

4.0%
Traffic Growth

49,405
2040 Fleet

2.1M
New Personnel

$9,540B
Services Market Value

North America
9,160 Deliveries
2040 Total Fleet: 10,835
Services Market Value: $2,070B

Europe
8,705 Deliveries
2040 Total Fleet: 9,140
Services Market Value: $1,895B

Russia and
1,540 Deli
2040 Total Fleet
Services Market

Service

Latin America
2,530 Deliveries
2040 Total Fleet: 3,095
Services Market Value: $535B

Africa
1,030 Deliveries
2040 Total Fleet: 1,560
Services Market Value: $235B

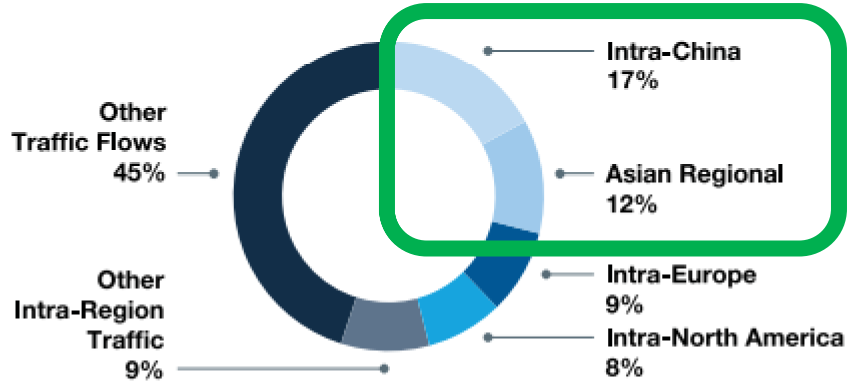
Middle East
3,000 Deliveries
2040 Total Fleet: 3,530
Services Market Value: $740B

Asia-Pacific*
8,945 Deliveries
2040 Total Fleet: 9,520
Services Market Value: $1,945B

*Does not include China

| 3

Forecast shares of traffic growth, by flow



>1/4 of commercial aircraft deliveries are planned in Asia

Brief historical aircrafts review

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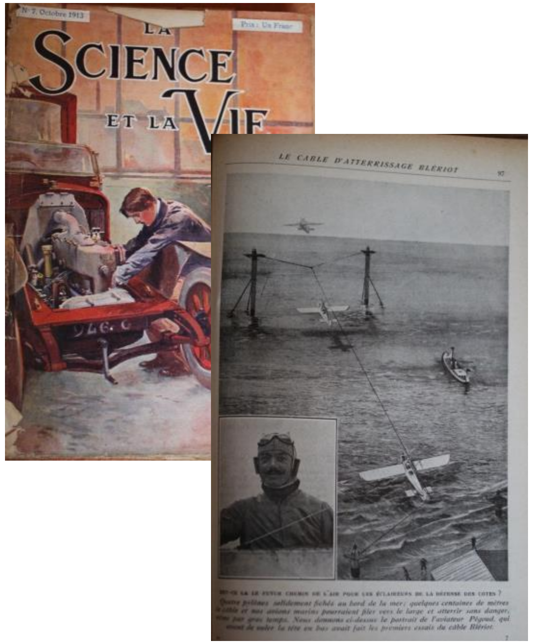
#Flying1913



Ing. Blériot
Cable launch

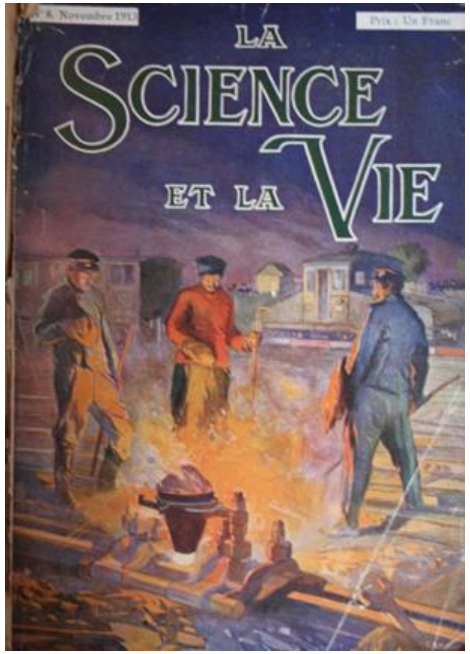
Single wing/body

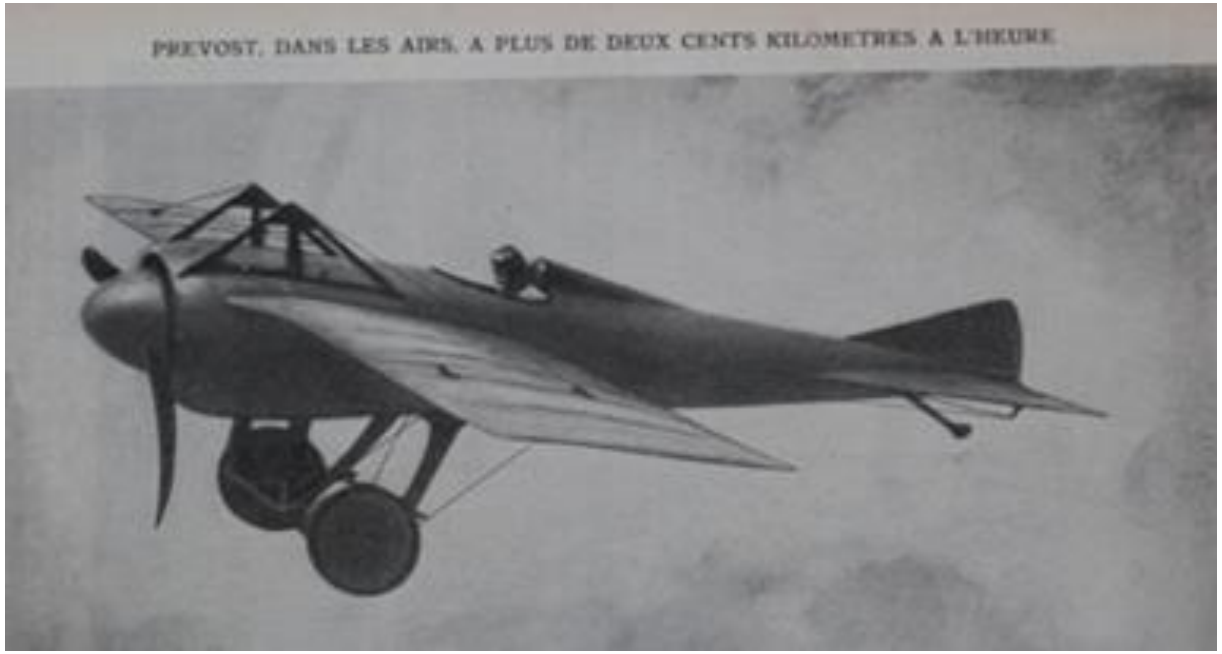
No wing shrouds

Ing Eiffel
Wind Tunnel

Before WW1, progress are made on :
engine power, aerodynamic shapes, wind tunnel understanding

#Flying1913 – Single body shape





PREVOST, DANS LES AIRS, A PLUS DE DEUX CENTS KILOMETRES A L'HEURE

Notre figure représente le monocoque de l'ingénieur Béchereau en plein vol. Cet appareil est remarquable non seulement parce qu'il a permis à Prévost de parcourir 200 kilomètres en moins d'une heure, mais encore parce qu'il se distingue nettement de tous les types d'aéroplanes établis jusqu'alors, tant par son mode de construction que par son aspect extérieur.

Single wing/body at 200km/hour

#Flying1943 – After WW1 and WW2

Source image : Wikipedia

Lockheed L-1649 Constellation « Starliner » of Trans World Airlines (TWA)

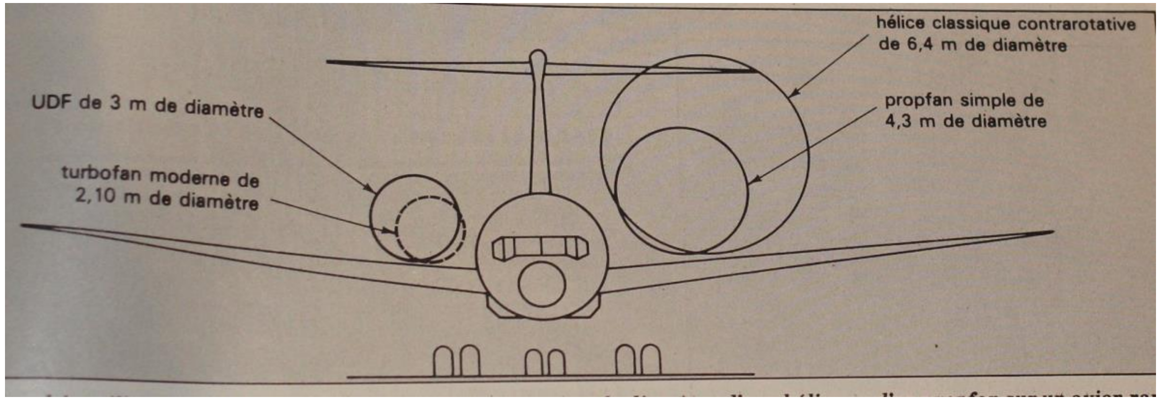
- 4 engines (but called « best 3 engines plane »)
- 3 Vertical drift planes (for storage height)
- Fuselage is not cylindrical
- Hydraulic assisted commands
- Max speed 550km/h, cruise speed 480 km/h

Commercial aviation is starting after WW2

#Flying1983

Wings, engines and stabilizers places ?

Open rotors ?

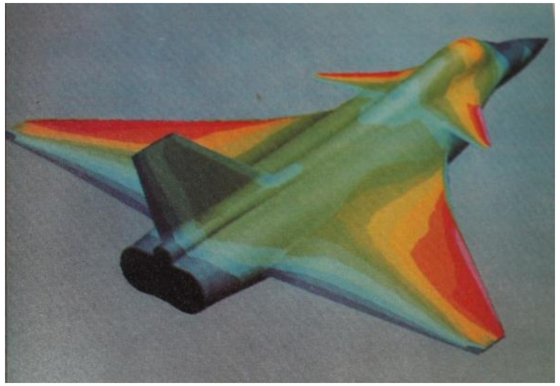


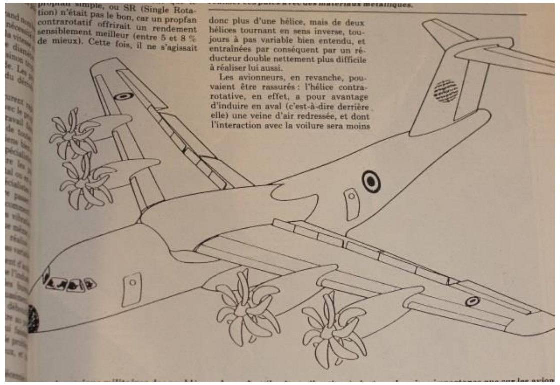
Engines places ?

Those studies are still under investigation, today in 2020+

Radical Configuration Flight Test Demonstrator

#Flying1983





- Developpment of numerical design tools (CATIA by Dassault System)
- Aircraft familly (cockpit ergonomy)

Numerical simulation tools have been and still are a revolution in aircraft design

#Flying2019

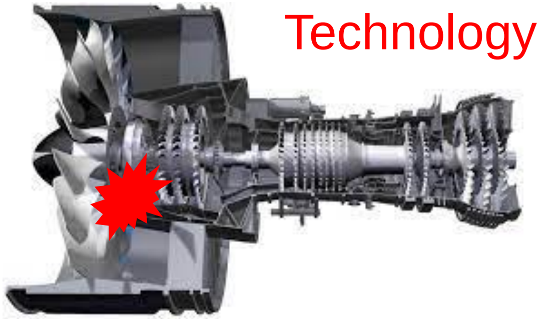
A320 neo

A350

A380


Size / Market

PW1000G


Technology

B737 max

Shape problem

B787

A400m

DA Falcon 5X / Silvercrest


Dev. engine

Even today, aircraft and engines developpement is still hazardious for large players

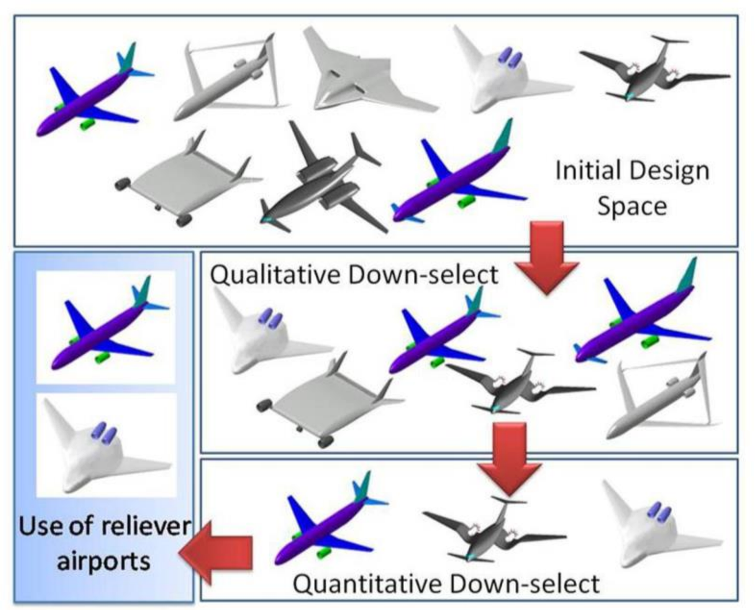
#Flying2019

What is an aircraft today or in the future ?

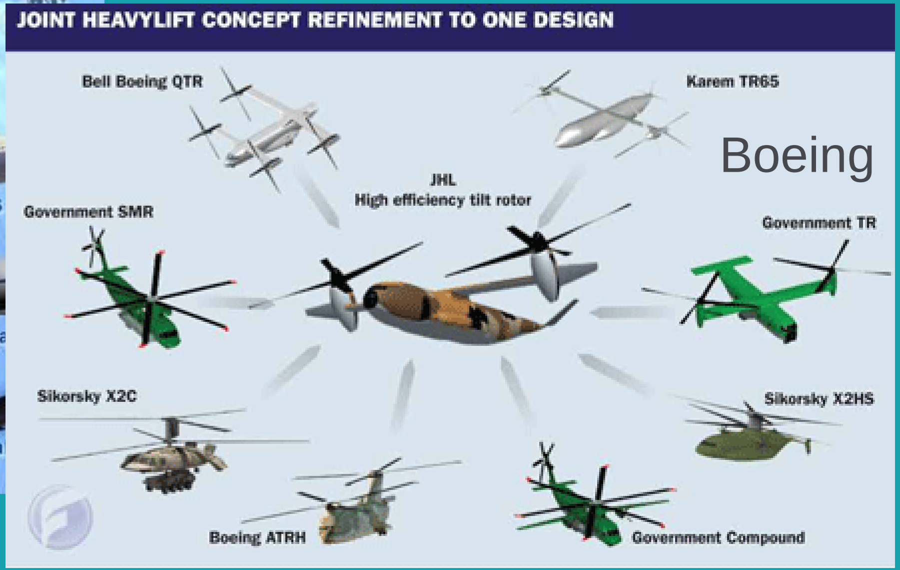
- 5% of the aircraft value is final assembly
- 35% of the total flight cost by hour are engines and consomption

What is the value for passengers, where is the added-value ?

Design space for future aircraft



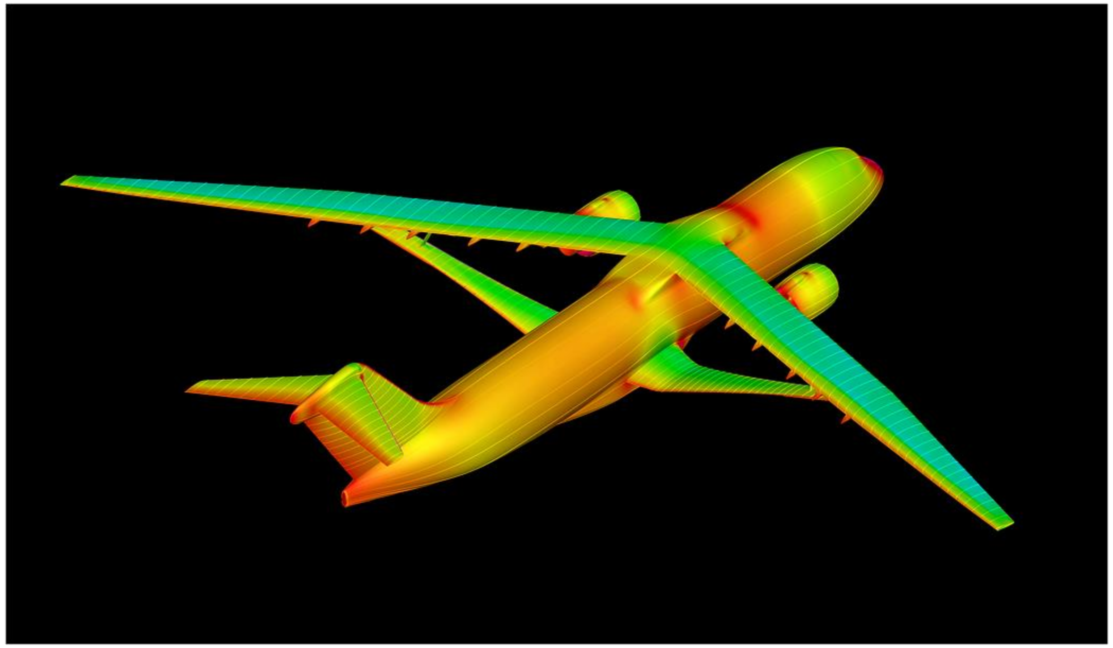
Nasa



Boeing

Most studies are made on exotic shapes
Most aircrafts are delivered within regionnal and single aisle categories

#Flying2050 ?



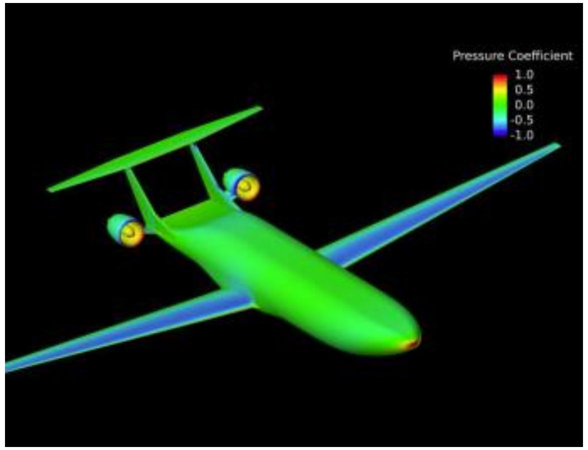
Artist illustration of the X-59 Quiet SuperSonic (Lockheed Martin)

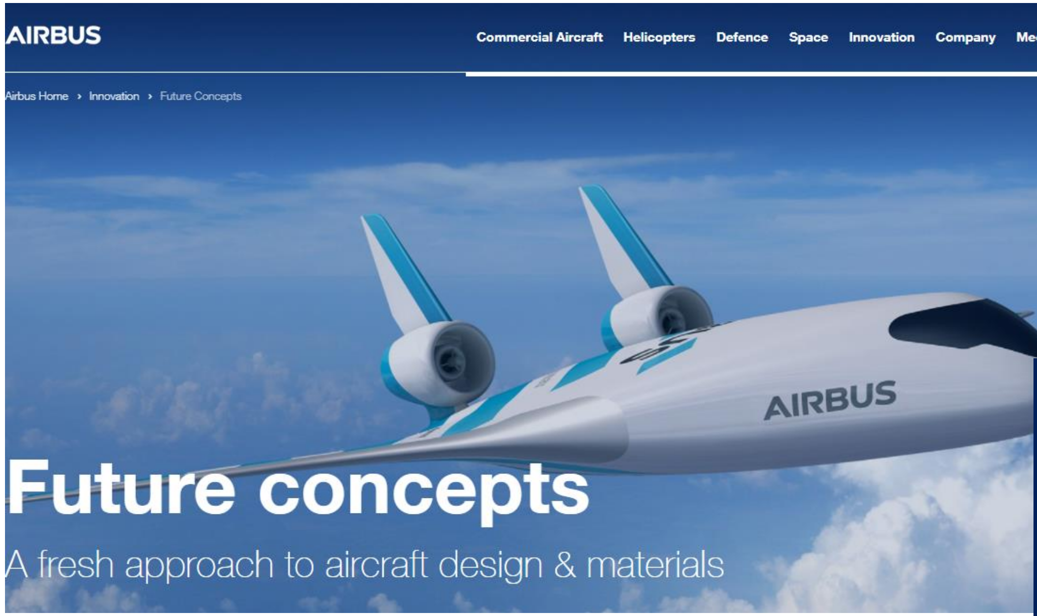
#Flying2050 ?


The Future of the Aircraft Cabin
Tracking Trends and Debunking Myths


© AIRBUS S.A.S. 2009 - COMPUTER RENDERING BY FIXION - GAUNSO


LOCKHEED MARTIN


Pressure Coefficient
1.0
0.5
0.0
-0.5
-1.0



Future concepts

A fresh approach to aircraft design & materials

AIRBUS

Our disruptive design projects

MAVERIC

This game-changing "blended wing body" design could generate up to 20% less fuel burn compared to current single-aisle models with the same engine. The exceptionally spacious layout also opens up the design space, enabling the possible integration of various other types of propulsion systems.

Racer

This helicopter demonstrator's advanced design means it will be 10-15% more efficient than standard helicopters. It has the potential to reach speeds of 400 Km/h, which is significantly faster than standard helicopters.

Future Combat Air System (FCAS)

This European defence programme aims to connect the next-generation fighter aircraft to other aerial vehicles through a system-of-systems approach.

Airbus AI

ASTARTES

The Air Superiority Tactical Assistance Real Time Execution System is an Artificial Intelligence (AI) project that aims to digitise the human-level experience to support operators with their tactical coordination tasks in the context of the Future Combat Air System (FCAS).

Autonomous flight

Computer vision and machine-learning technologies based on AI are critical to enabling self-piloted commercial aircraft to take off and land, and to navigate and detect ground obstacles autonomously.

CIMON

This AI-based robotic assistant for astronauts aboard the International Space Station is equipped with cameras, sensors and microphones to see, hear, process and display information, as well as speak and fly.

Earth observation

Imagery provided by advanced aerospace technologies – such as high-resolution satellites and drones within an AI environment – can generate customised analyses for applications relating to catastrophe response and damage assessment.

Factory of the Future

This DDMS project aims to standardise and streamline software AI tools used for enterprise resource planning to move from sequential to co-developmental production processes.

Future Combat Air System (FCAS)

This European defence programme aims to connect the next-generation fighter aircraft to other aerial vehicles through a system-of-systems approach that is enabled by advanced analytics and AI.

Skywise

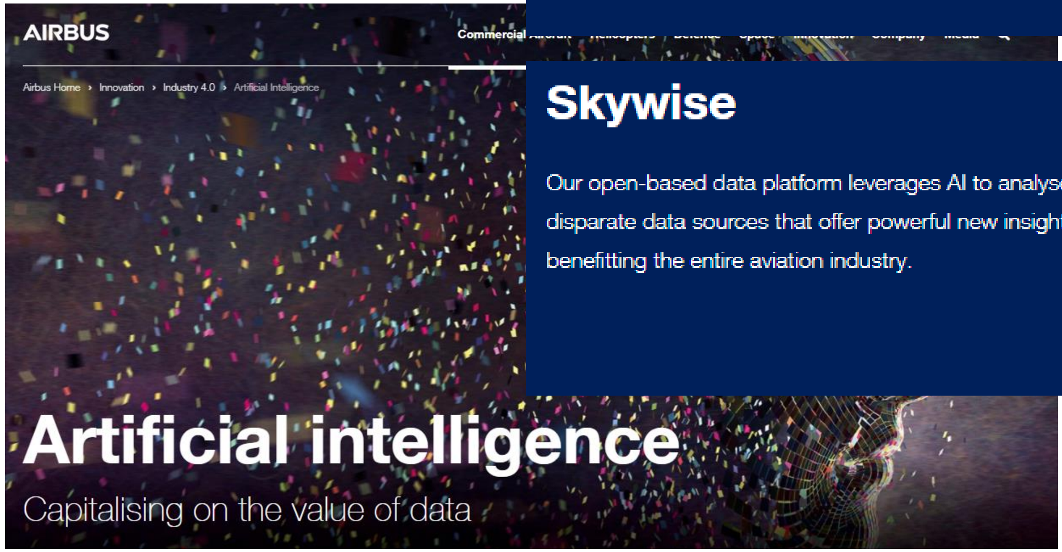
Our open-based data platform leverages AI to analyse disparate data sources that offer powerful new insights benefitting the entire aviation industry.

Unmanned Traffic Management

When sharing our airspace, today's unmanned aerial vehicles, such as drones, exchange vast amounts of mission-critical information – all of which AI can filter, classify and merge.

Urban Air Mobility

Sense-and-avoid technology, built on AI, leverages mission-critical data to enable self-piloting future air mobility vehicles to predict and react to unforeseen scenarios.



Artificial intelligence

Capitalising on the value of data

AIRBUS

Artificial intelligence in aeronautics

demos
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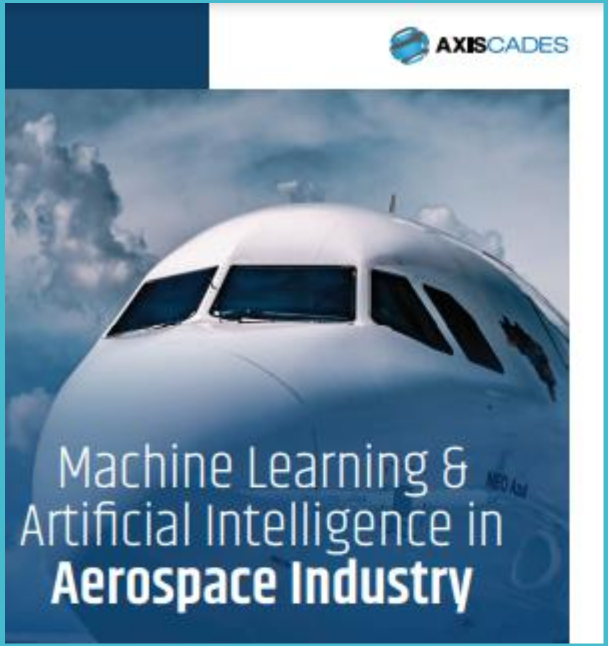
Studies of IA usage in aeronautics

https://www.axiscades.com/blog-resources/whitepaper/Aerospace-whitepaper.pdf


AXISCADES

Machine Learning & Artificial Intelligence in **Aerospace Industry**

Here are the top areas that AI is being used by aerospace manufacturers today:

- Predictive Maintenance
- Optimized flight performance
- Generative design
- Efficient supply chain management
- Improved quality control
- Training

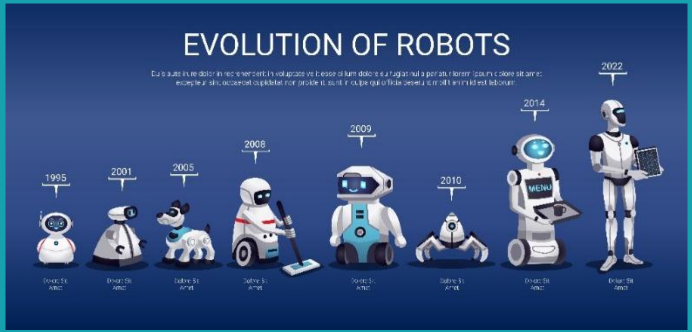
Today most usages are Big Data problems

Why aeronautics is not yet using IA ?

In aeronautics, most algoritms have to be **determinist**
To achive high level of **reliability** and repeatability

Robots and IA - State of the art on the ground

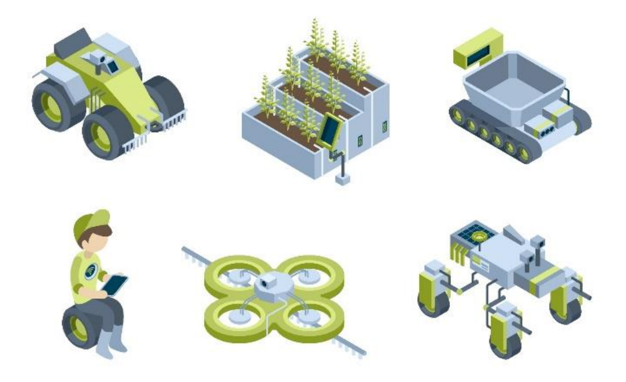
Urban Air Mobility



Daily life robots

Transportation

Deliveries

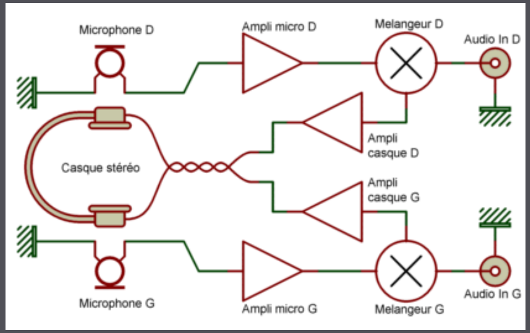


Farming automation

Automotive industry

Security

IA usages



Noise cancelling headphone

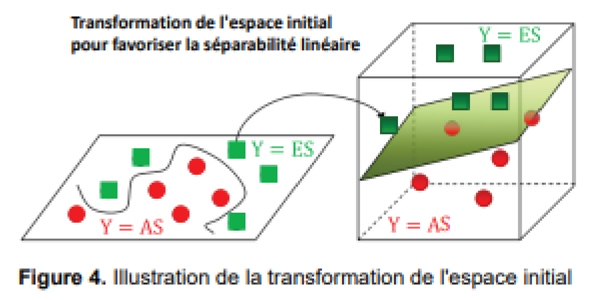


Figure 4. Illustration de la transformation de l'espace initial

Data sorting


Airbus PRESS
@AirbusPRESS

.@Airbus launches advanced indoor inspection drone to reduce aircraft inspection times and enhance report quality airbus.com/newsroom/press ... @testia

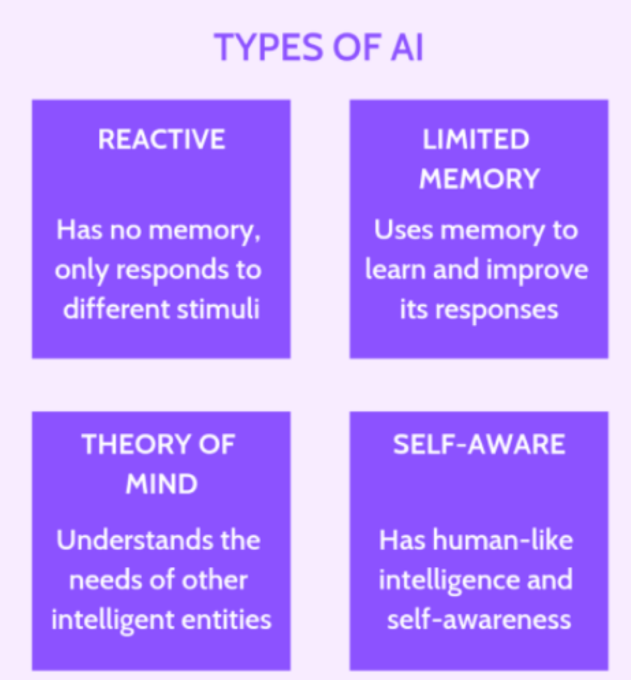
Airplane inspection

Air traffic management

Levels of AI

Forbes

https://www.forbes.com/sites/cognitiveworld/2019/06/19/7-types-of-artificial-intelligence/?sh=3d23a43e233e



TYPES OF AI

REACTIVE

Has no memory, only responds to different stimuli

LIMITED MEMORY

Uses memory to learn and improve its responses

THEORY OF MIND

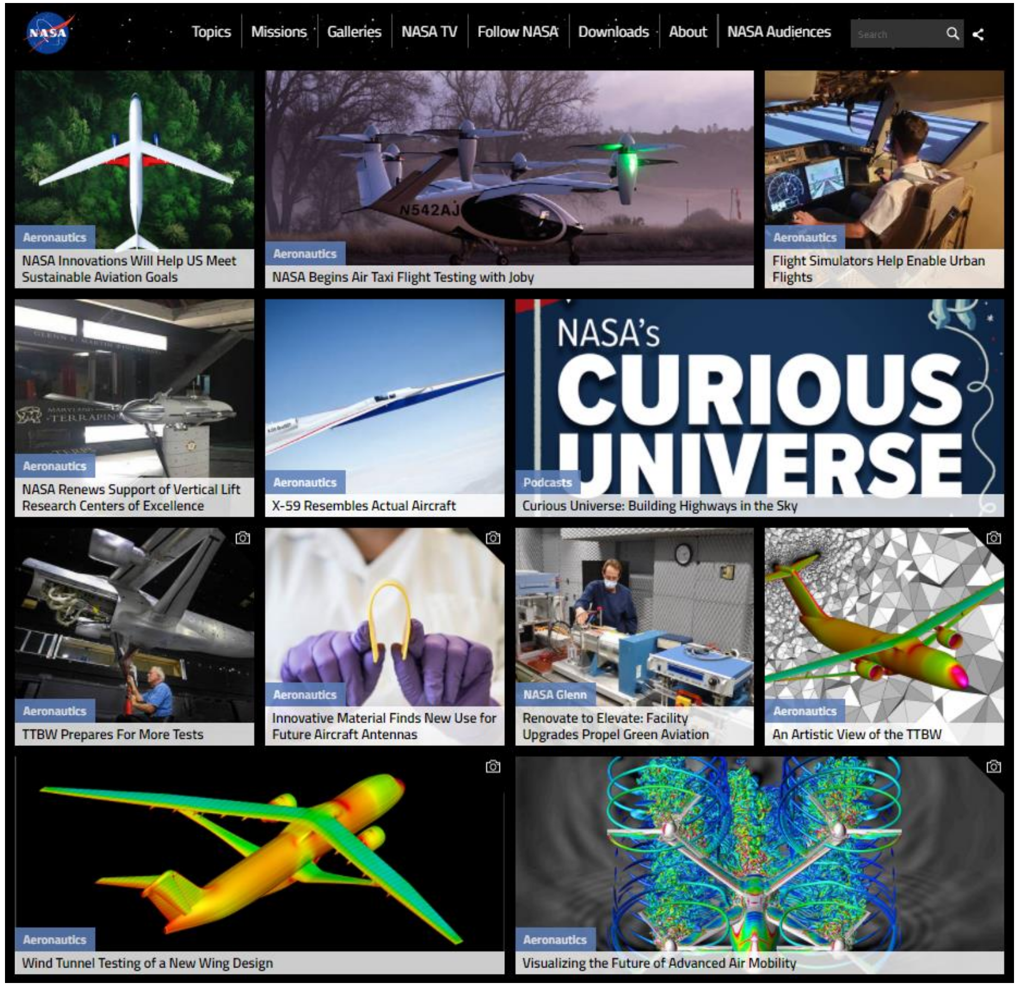
Understands the needs of other intelligent entities

SELF-AWARE

Has human-like intelligence and self-awareness

1. **Reactive Machines**
2. **Limited Memory**
3. **Theory of Mind**
4. **Self-aware**
5. **Artificial Narrow Intelligence (ANI)**
6. **Artificial General Intelligence (AGI)**
7. **Artificial Superintelligence (ASI)**

Nasa future aircraft technologies



Aeronautics
NASA Innovations Will Help US Meet Sustainable Aviation Goals

Aeronautics
NASA Begins Air Taxi Flight Testing with Joby

Aeronautics
Flight Simulators Help Enable Urban Flights

Aeronautics
NASA Renews Support of Vertical Lift Research Centers of Excellence

Aeronautics
X-59 Resembles Actual Aircraft

Podcasts
Curious Universe: Building Highways in the Sky

Aeronautics
TTBW Prepares For More Tests

Aeronautics
Innovative Material Finds New Use for Future Aircraft Antennas

NASA Glenn
Renovate to Elevate: Facility Upgrades Propel Green Aviation

Aeronautics
An Artistic View of the TTBW

Aeronautics
Wind Tunnel Testing of a New Wing Design

Aeronautics
Visualizing the Future of Advanced Air Mobility

https://www.nasa.gov/subject/7565/future-aircraft/

Your pilot is a robot !

Two human pilots

Autonomous robot

0 human pilots on board

Auto-pilot

COBOT

No cockpit ?

Constrains are failure modes :

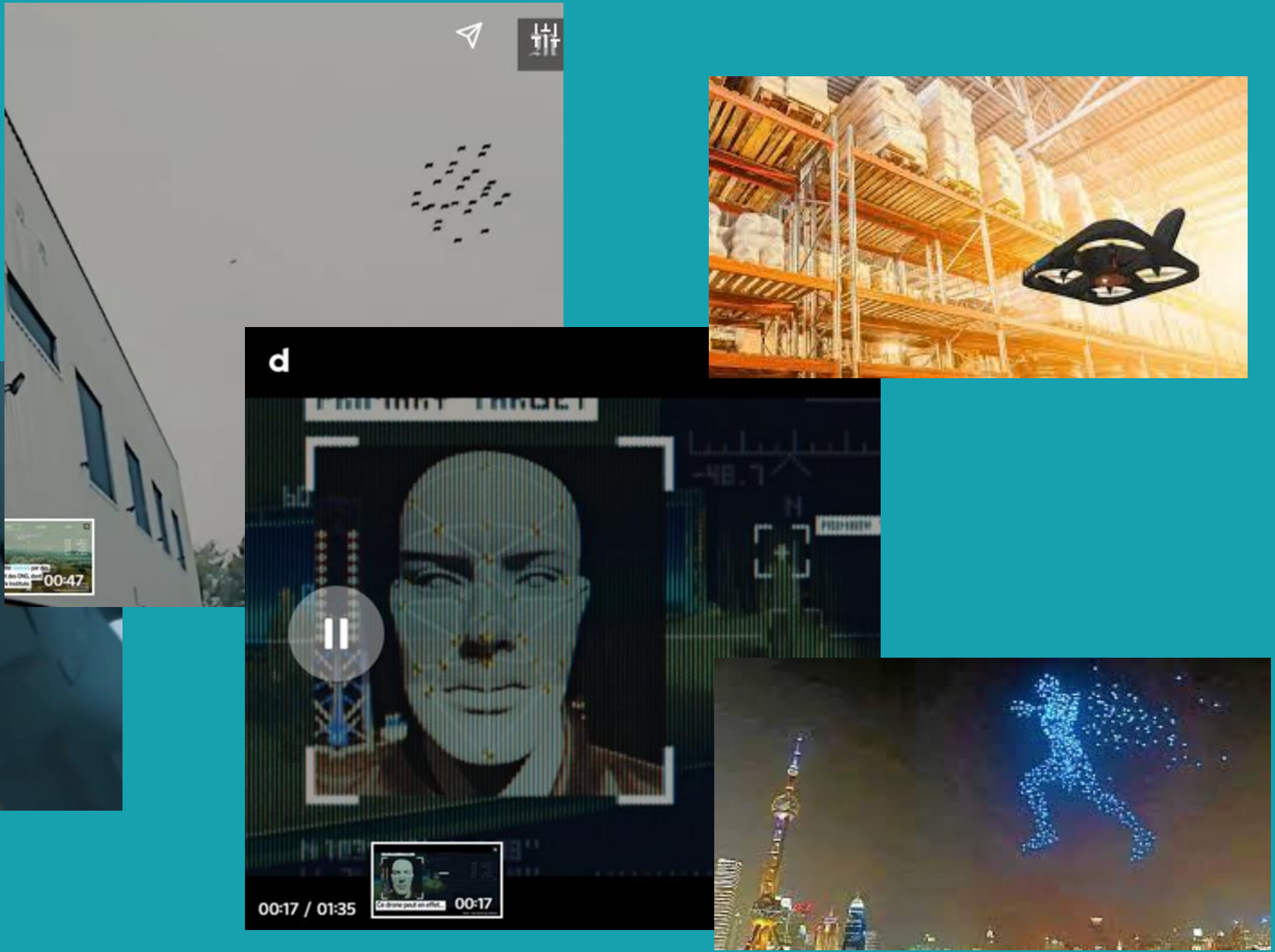
human errors, mission changes, aircraft maintenance issues (including engines)

1 pilot for a swarm of aircrafts ?

What is an aircraft ?

Technologies and algorithms are everywhere from development, production, to final usage

Drones swarm



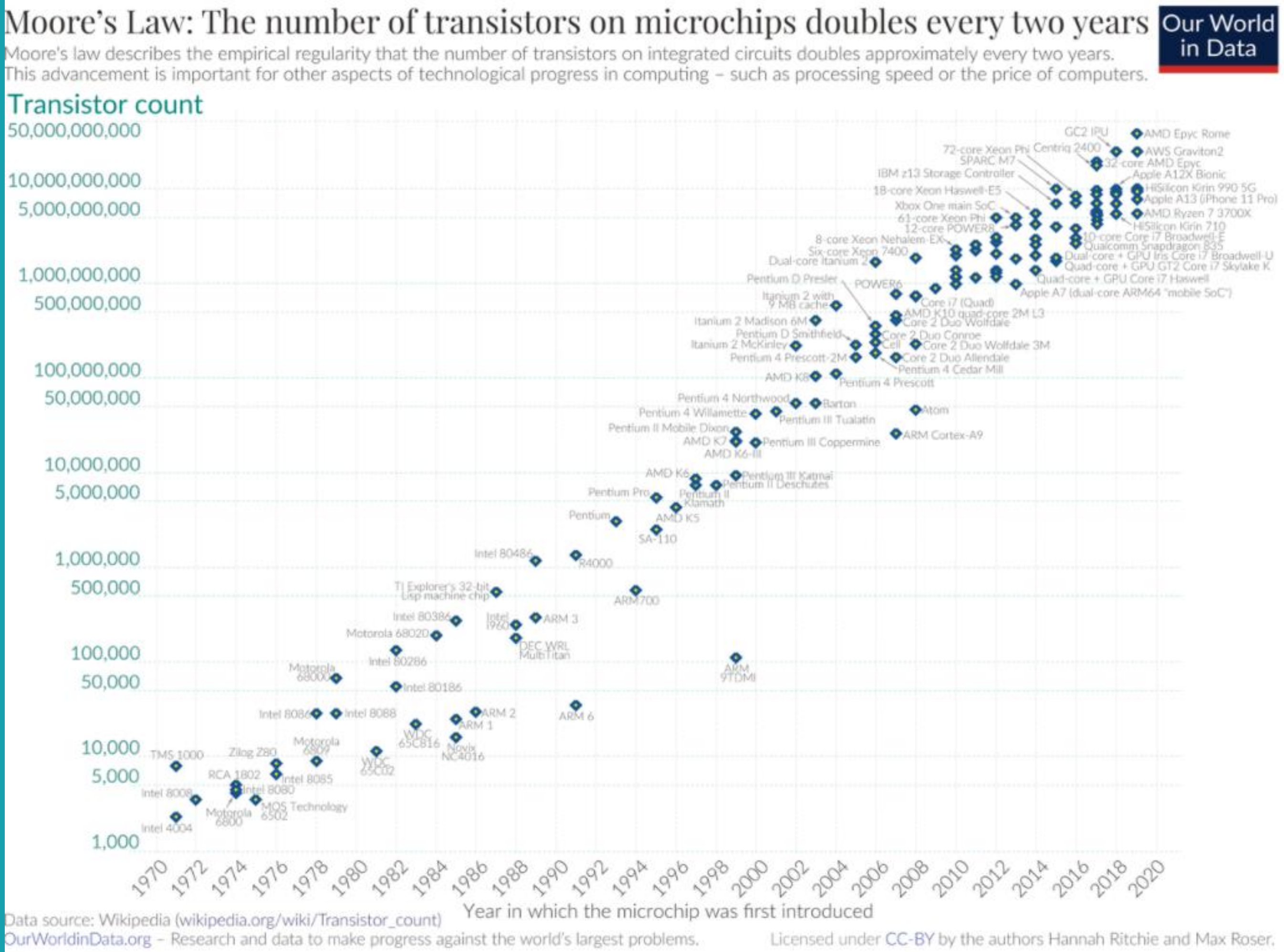
https://www.ted.com/talks/pw_singer_on_robots_of_war
/transcript?awesm=on.ted.com_Slavin&language=fr

Drones with embarked IA are already used, and usages will expand

Moore Law

- Calculation power is exponential
- Calculation power in a smart device (phone, tab) is already enough to pilot a plane

- R2D2 from Star Wars movie is able to pilot a space ship



Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

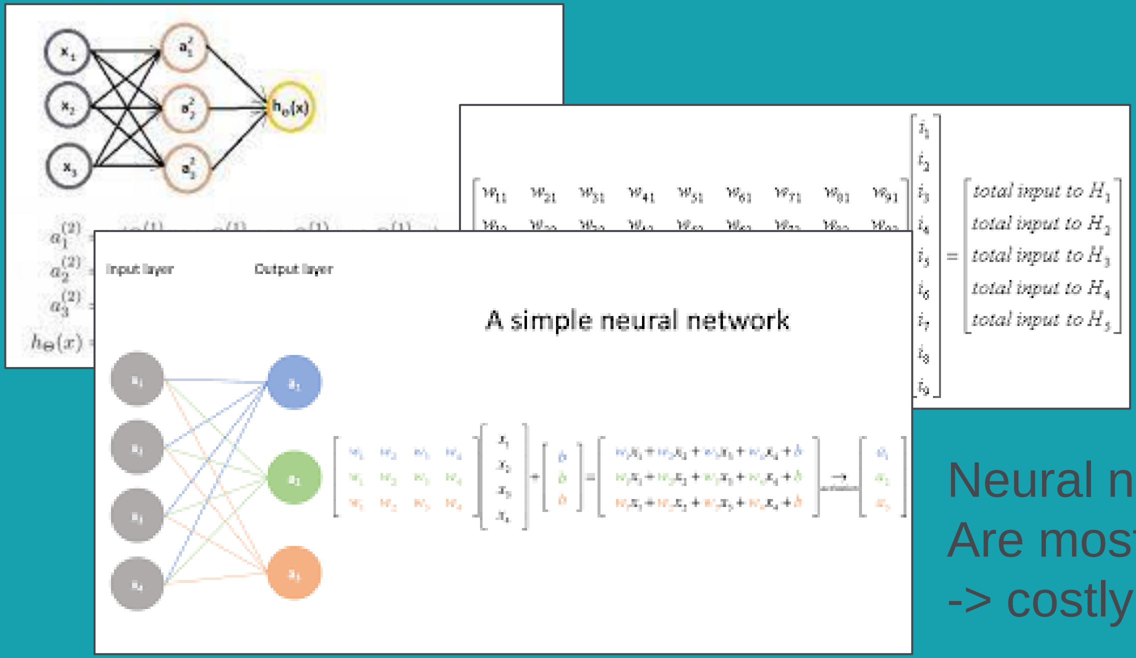
Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

https://fr.wikipedia.org/wiki/Loi_de_Moore

How IA Hardware will improve



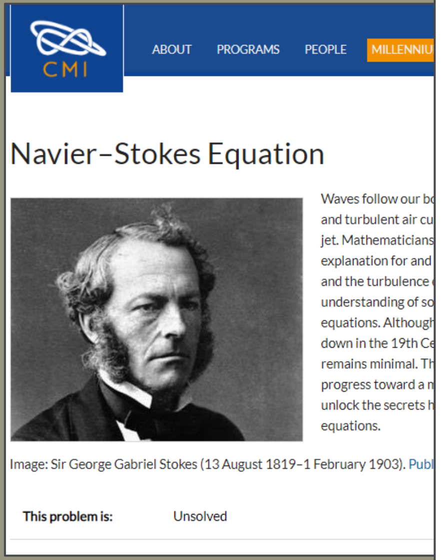
Neural network Algorithm
Are mostly coded with matrix
-> costly in calculation steps

Intel Nervana NNP
(Neural Network Processor)

IA will improve with dedicated hardware architecture (NNP)

Navier Stocks Equation – Millenium problem

https://www.claymath.org/millennium-problems/navier%E2%80%93stokes-equation



ABOUT PROGRAMS PEOPLE MILLENNIU

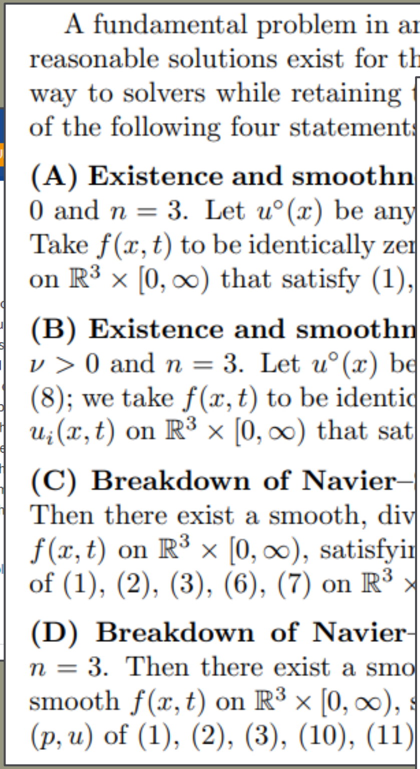
CMI

Navier–Stokes Equation

Waves follow our b
and turbulent air cu
jet. Mathematicians
explanation for and
and the turbulence
understanding of so
equations. Althoug
down in the 19th C
remains minimal. T
progress toward a
unlock the secrets
equations.

Image: Sir George Gabriel Stokes (13 August 1819–1 February 1903). Publ

This problem is: Unsolved



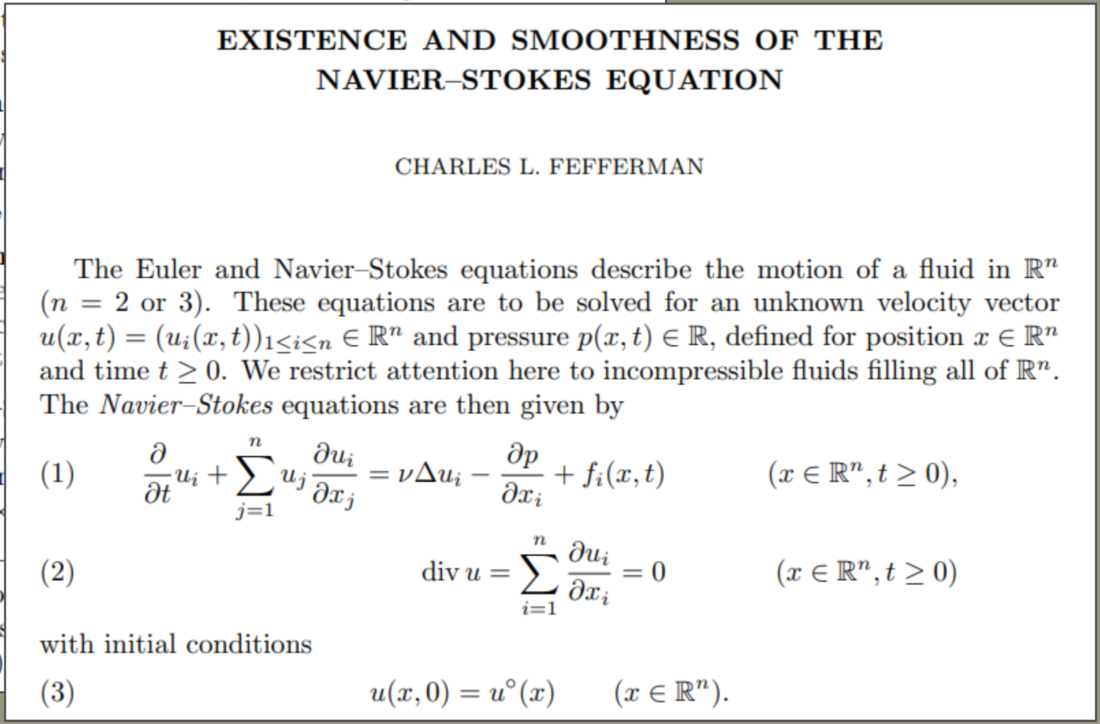
A fundamental problem in analysis is to decide whether such smooth, physically
reasonable solutions exist for the Navier–Stokes equations. To give reasonable lee-
way to solvers while retaining
of the following four statement

(A) Existence and smoothn
0 and $n = 3$. Let $u^\circ(x)$ be any
Take $f(x,t)$ to be identically ze
on $\mathbb{R}^3 \times [0,\infty)$ that satisfy (1),

(B) Existence and smoothn
$\nu > 0$ and $n = 3$. Let $u^\circ(x)$ be
(8); we take $f(x,t)$ to be identic
$u_i(x,t)$ on $\mathbb{R}^3 \times [0,\infty)$ that sat

(C) Breakdown of Navier–
Then there exist a smooth, div
$f(x,t)$ on $\mathbb{R}^3 \times [0,\infty)$, satisfyi
of (1), (2), (3), (6), (7) on $\mathbb{R}^3$ ×

(D) Breakdown of Navier–
$n = 3$. Then there exist a smo
smooth $f(x,t)$ on $\mathbb{R}^3 \times [0,\infty)$,
(p,u) of (1), (2), (3), (10), (11)



EXISTENCE AND SMOOTHNESS OF THE NAVIER–STOKES EQUATION

CHARLES L. FEFFERMAN

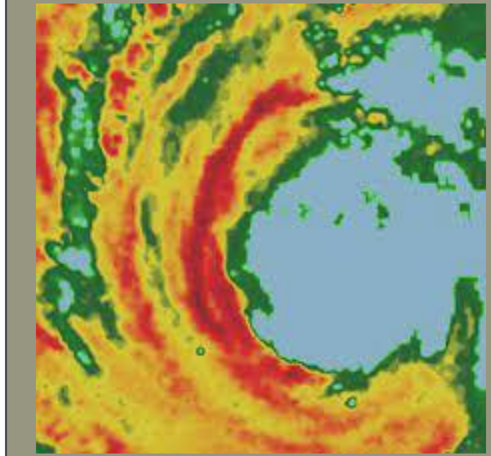
The Euler and Navier–Stokes equations describe the motion of a fluid in $\mathbb{R}^n$ ($n = 2$ or 3). These equations are to be solved for an unknown velocity vector $u(x,t) = (u_i(x,t))_{1 \le i \le n} \in \mathbb{R}^n$ and pressure $p(x,t) \in \mathbb{R}$, defined for position $x \in \mathbb{R}^n$ and time $t \ge 0$. We restrict attention here to incompressible fluids filling all of $\mathbb{R}^n$. The *Navier–Stokes* equations are then given by

$$\frac{\partial}{\partial t} u_i + \sum_{j=1}^{n} u_j \frac{\partial u_i}{\partial x_j} = \nu \Delta u_i - \frac{\partial p}{\partial x_i} + f_i(x,t) \qquad (x \in \mathbb{R}^n, t \ge 0), \tag{1}$$

$$\operatorname{div} u = \sum_{i=1}^{n} \frac{\partial u_i}{\partial x_i} = 0 \qquad (x \in \mathbb{R}^n, t \ge 0) \tag{2}$$

with initial conditions

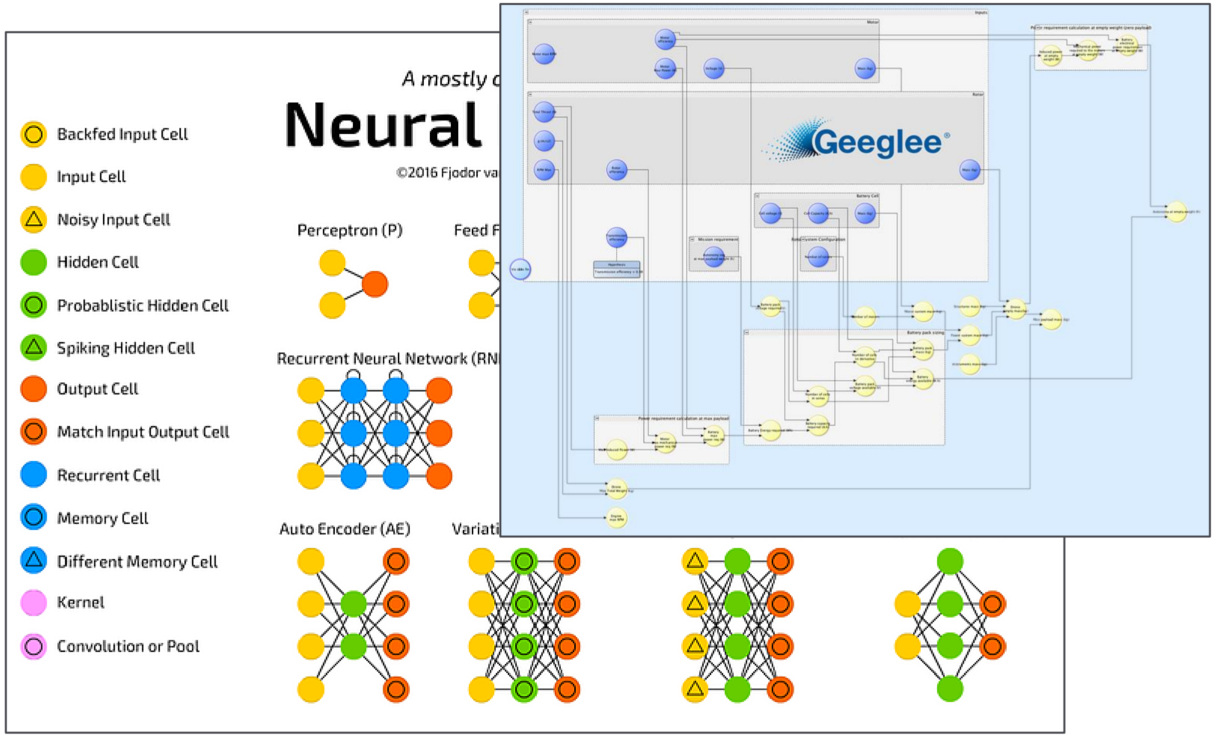
$$u(x,0) = u^\circ(x) \qquad (x \in \mathbb{R}^n). \tag{3}$$

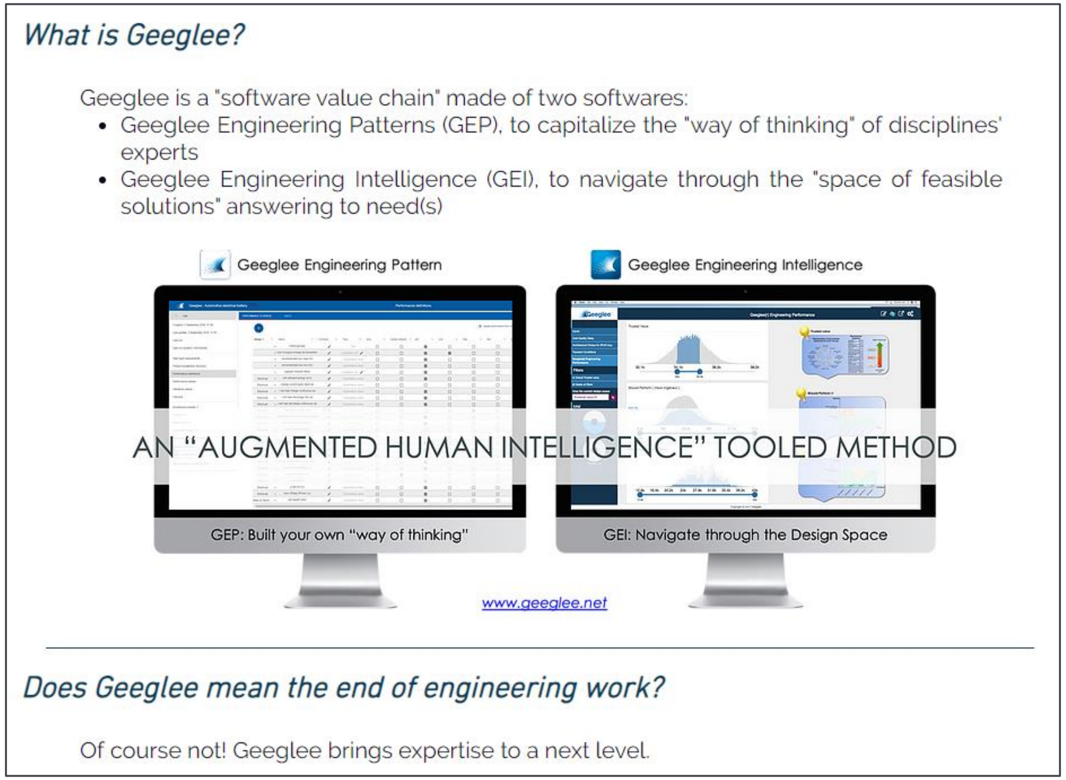


Difficult problems will need IA to speed up resolution

Engineering patterns and intelligence

http://www.geeglee.net/





What is Geeglee?

Geeglee is a "software value chain" made of two softwares:
- Geeglee Engineering Patterns (GEP), to capitalize the "way of thinking" of disciplines' experts
- Geeglee Engineering Intelligence (GEI), to navigate through the "space of feasible solutions" answering to need(s)

Geeglee Engineering Pattern

Geeglee Engineering Intelligence

AN “AUGMENTED HUMAN INTELLIGENCE” TOOLED METHOD

GEP: Built your own "way of thinking"

GEI: Navigate through the Design Space

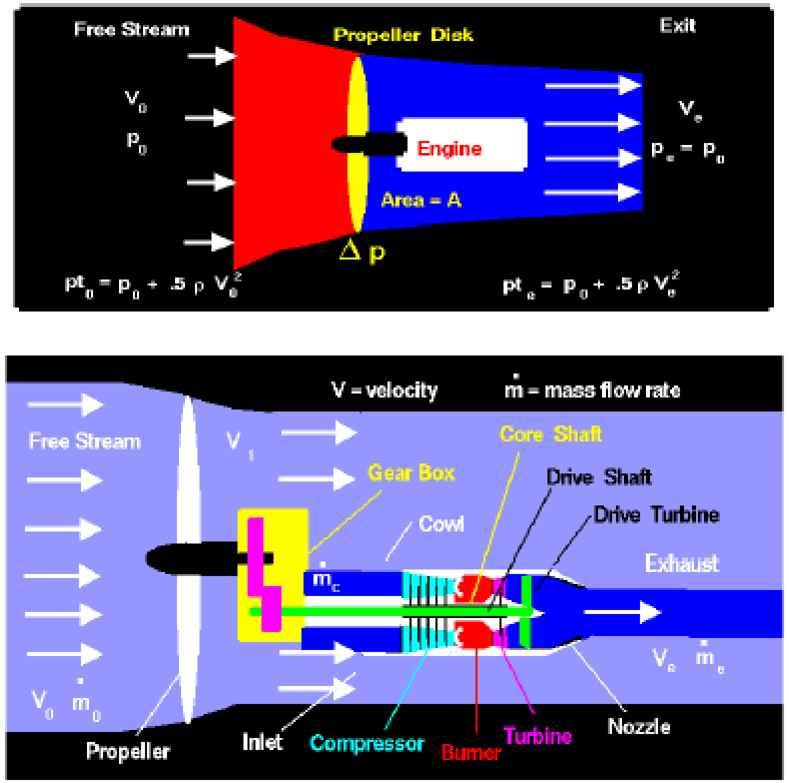
www.geeglee.net

Does Geeglee mean the end of engineering work?

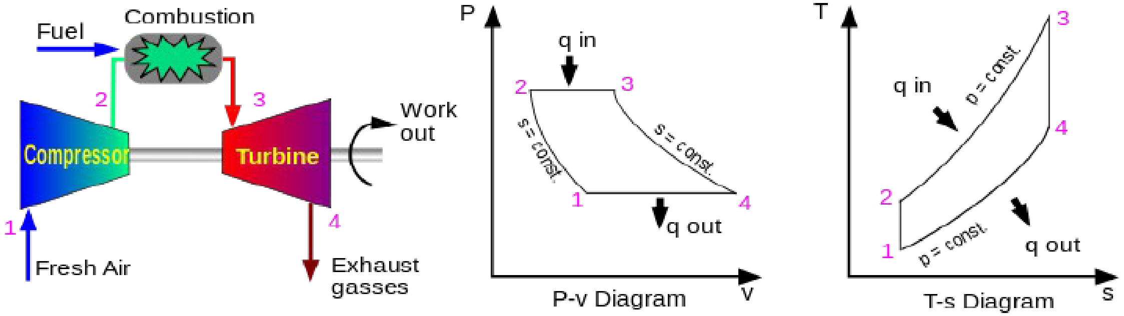
Of course not! Geeglee brings expertise to a next level.

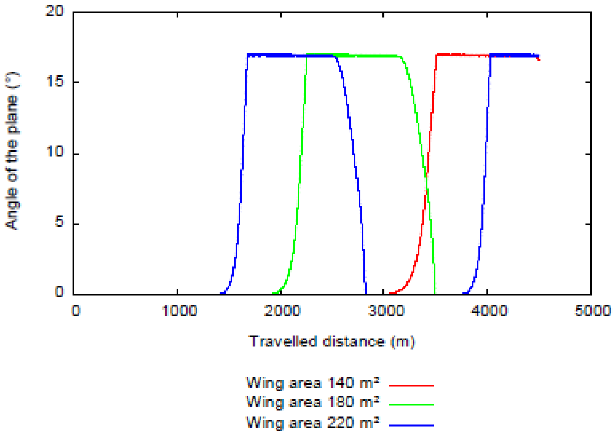
Data and algorithm architecture is key in the problem resolution

Engines simulation

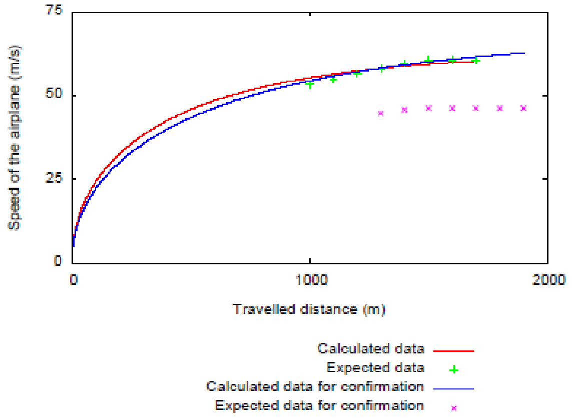


Engine models





Results V.2: Angle of the plane with a flap that add 100% of the lift coefficient and an initial wing angle of 3°

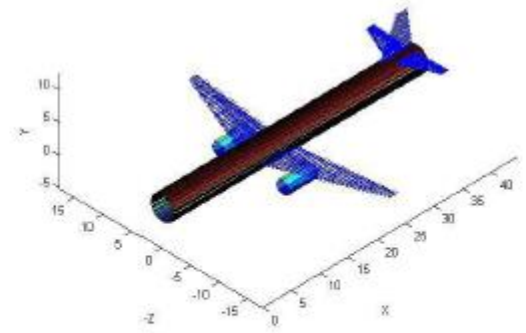


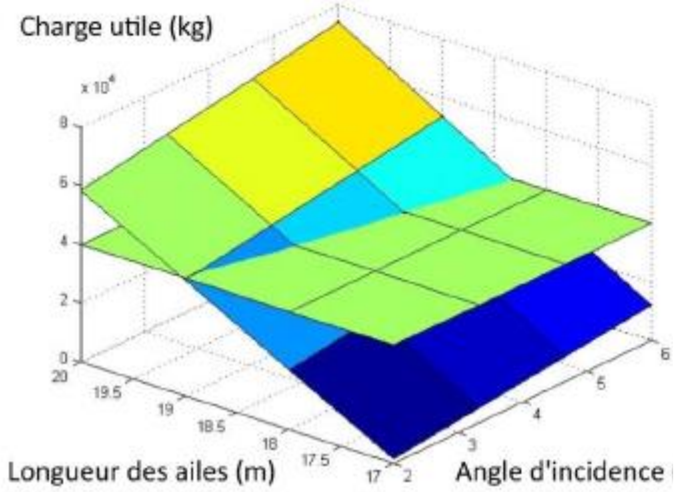
Results IV.2: Speed of the ATR72 obtained with the new model

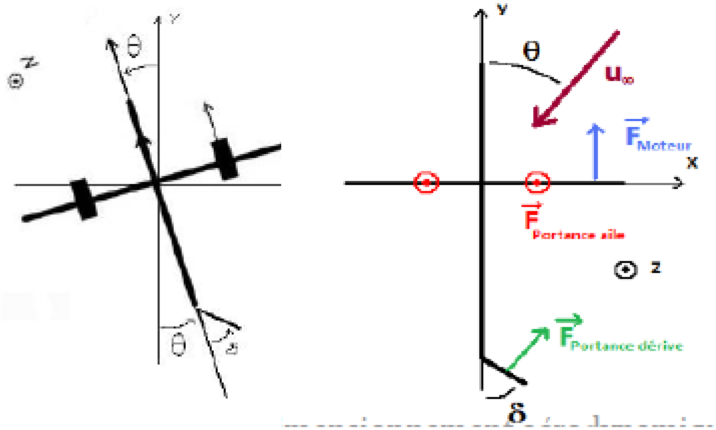
Complex aircraft modeling does not need IA (eg. hybrid engines)

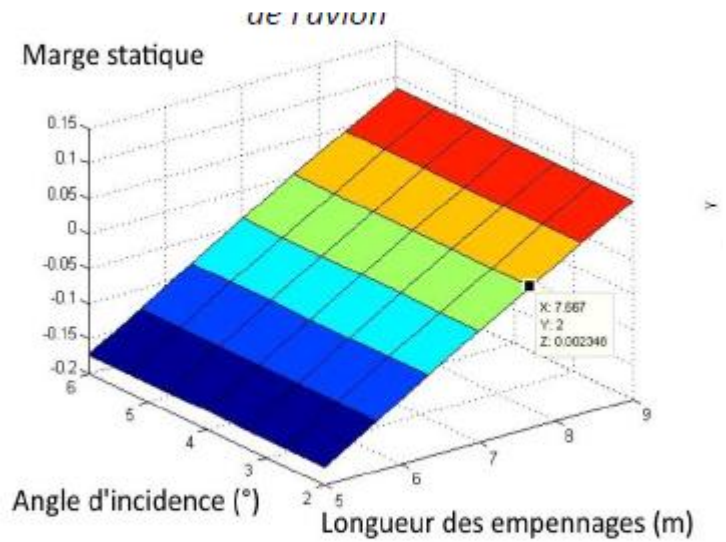
Basic aircraft flight simulation

CentraleSupélec







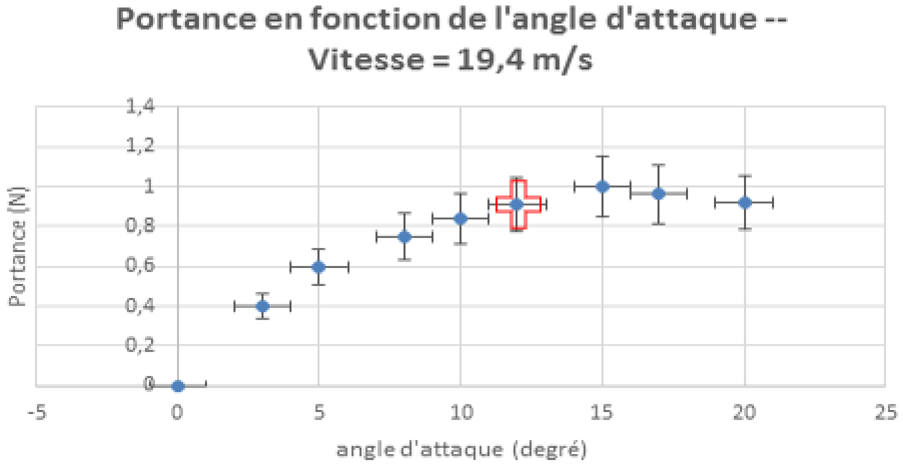


Multi form aircraft simulation does not need IA (eg. Multi wings)

Wing shape

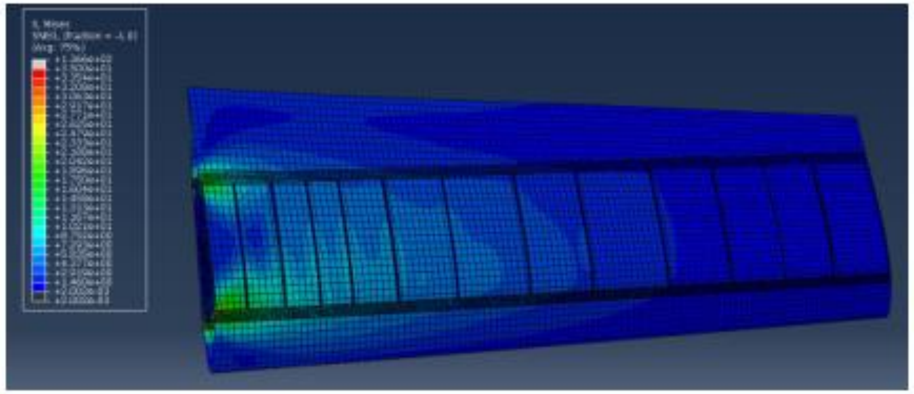
Hypothesis :

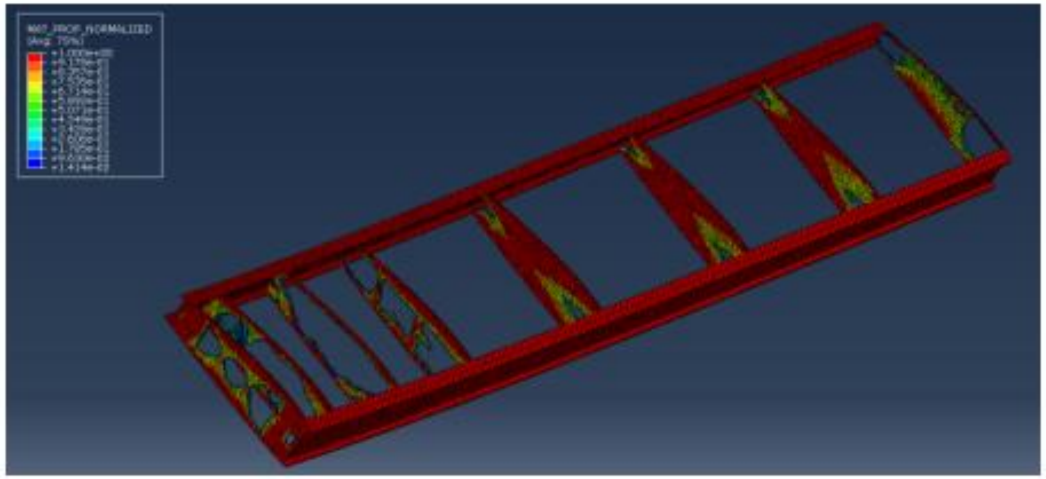
- Aircraft are using vertical air forces to balance weight
- Compromize between take-off and cruse flight
- Aircraft design is made according to crash condition



Aerodynamic parameters does not need IA

Topological wing optimization



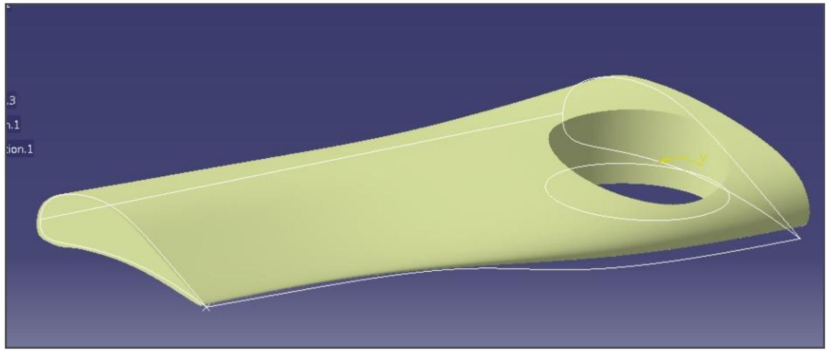


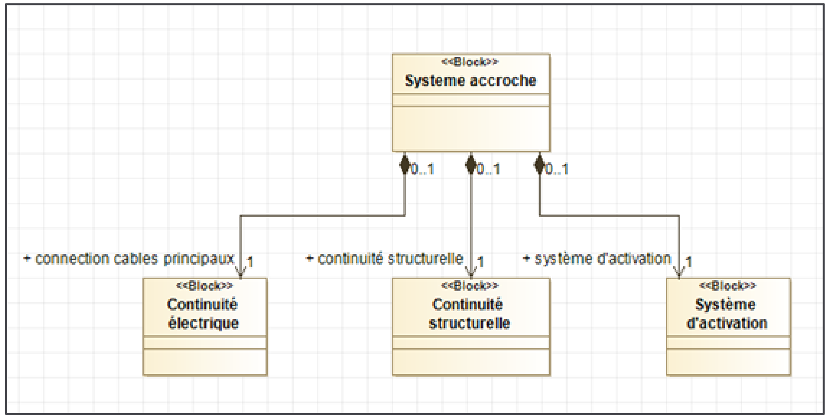
Basic optimization IA is already implemented within design software

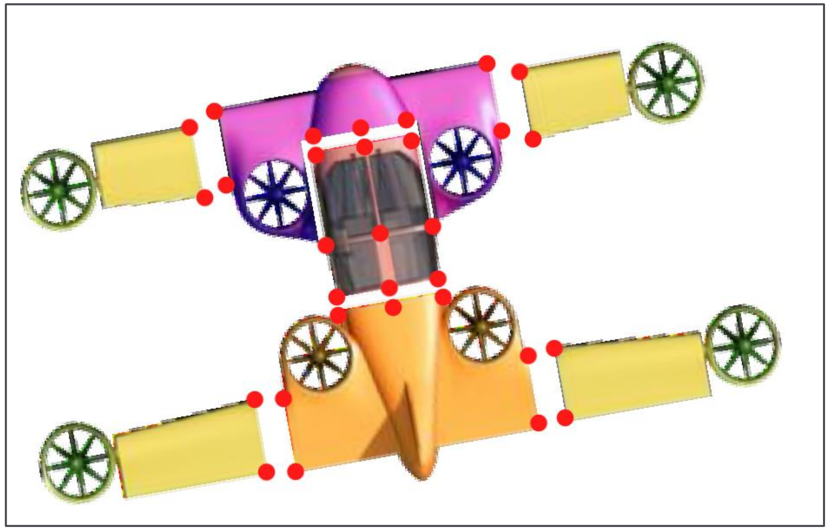
But IA integration within aircraft design is deficult due to multicriteria optimization

Multifonctionnal design is mandatory (structure, aerodynamic, equipement)

Production and maintenance issues versus initial design







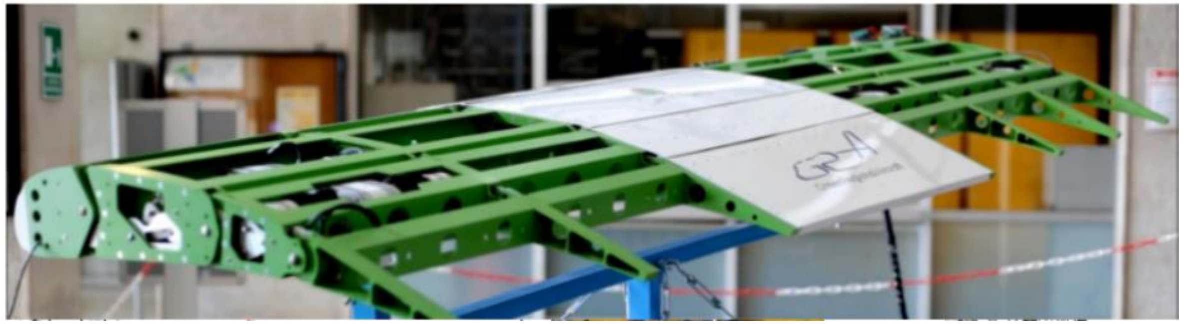
Example : wing optimisation in regard of modular conception

Aircraft design has to balance objectives :
- Weight & drag reduction
- Cost of production
- Equipements constraints
- Maintenance issues

Morphing wings

Flaps are already a basic morphing wing

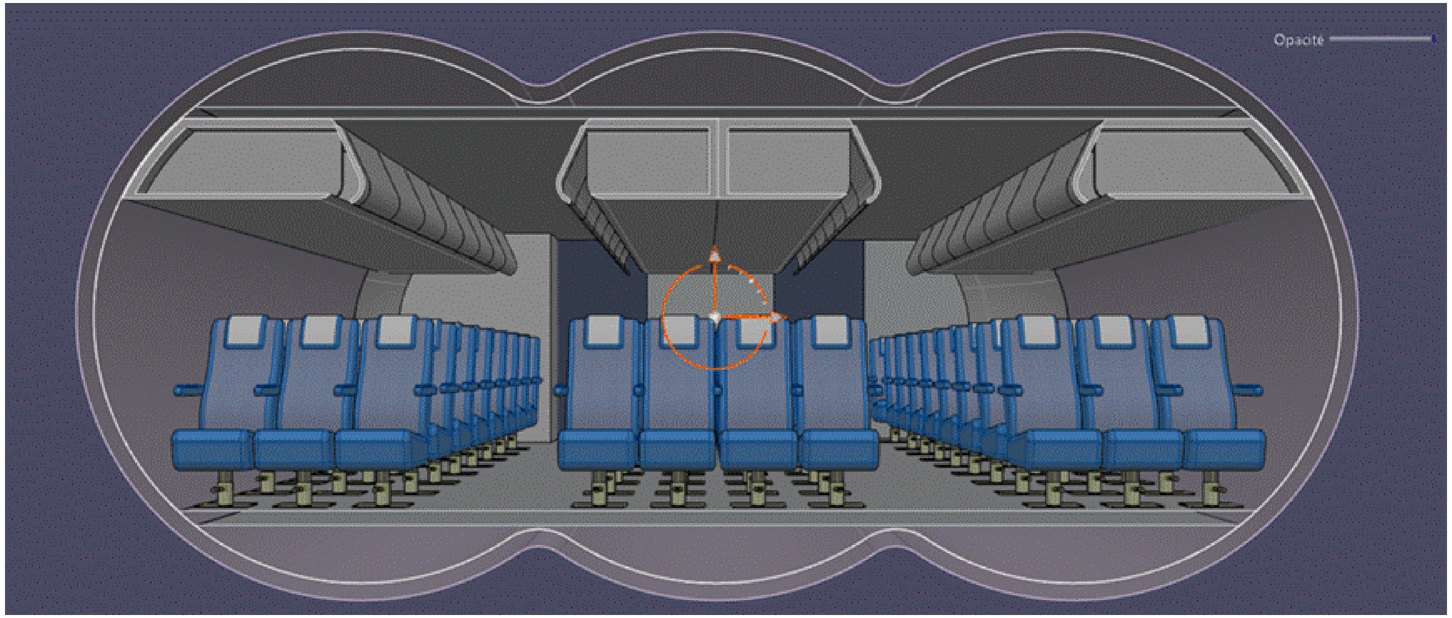
https://www.cleansky.eu/sites/default/files/inline-files/CS_Award_PhD_Francesco_Rea.pdf



Maintenance issues have to be overtaken

Reliability is key to assure operation high availability

Structural optimization



Cabin and fuselage optimization need to take into consideration passenger logistic experience

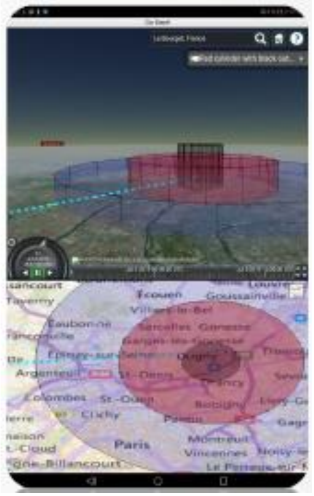
- Landing gear width

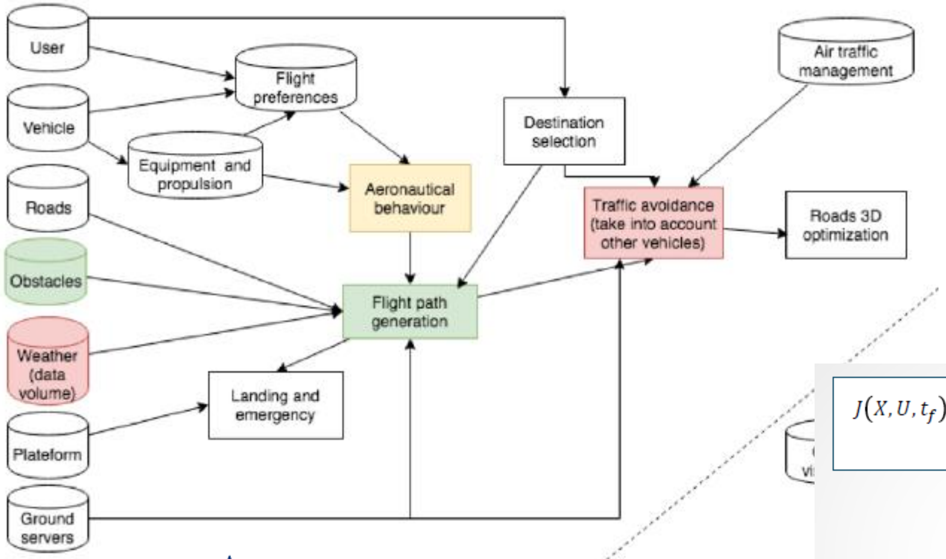
- Structural optimization
- Internal noise

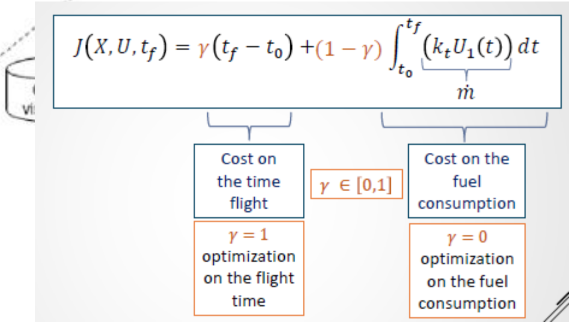
IA Example : Urban Air Mobility
Flight path optimization

Learning is changing®

Example : urban air mobility – Flight path optimization







$$J(X,U,t_f) = \underbrace{\gamma\left(t_f - t_0\right)}_{\text{Cost on the time flight}} + (1-\gamma)\int_{t_0}^{t_f} \underbrace{\left(k_t U_1(t)\right)}_{\dot{m}}\, dt$$

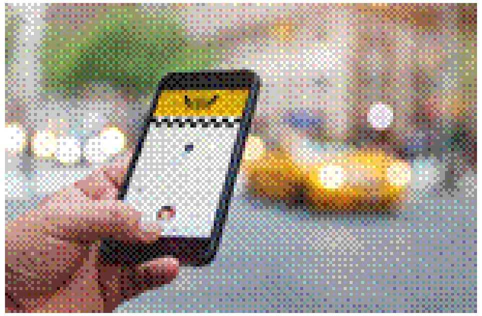
Cost on the the time flight

$\gamma \in [0,1]$

Cost on the fuel consumption

$\gamma = 1$ optimization on the flight time

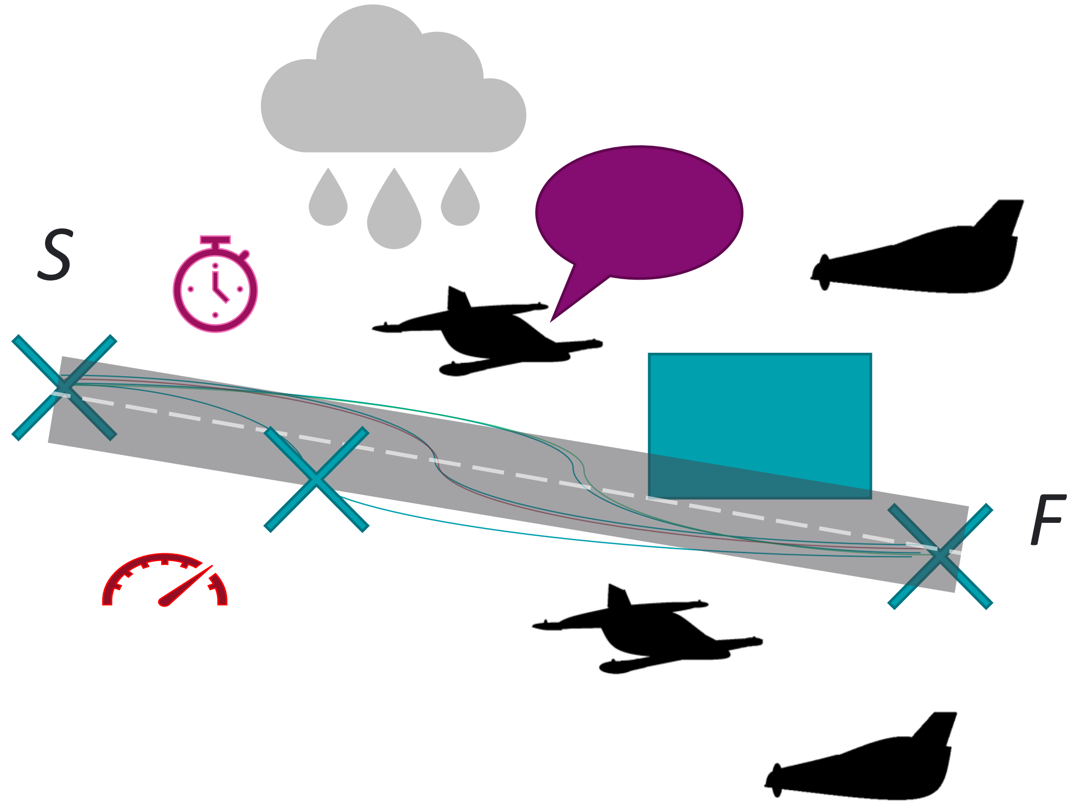
$\gamma = 0$ optimization on the fuel consumption



Problem is simple to formulated

Problem definition

Provide real time flight management information for the pilot or autopilot

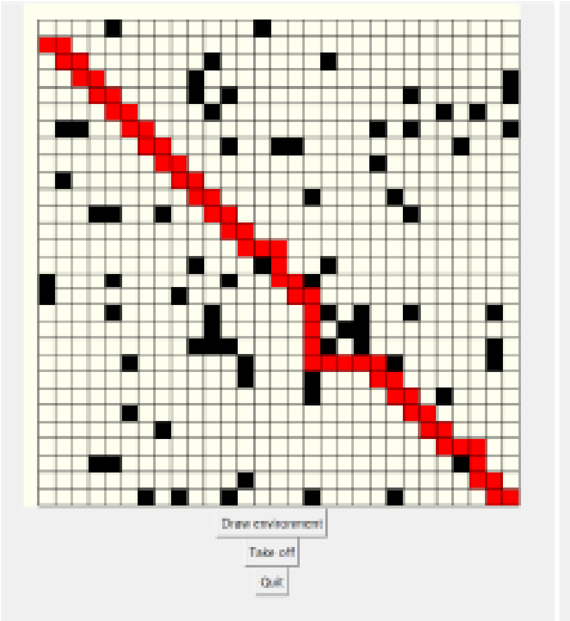


- Find an **eligible trajectory** from S to F in a **3D** environment
- Take **static obstacles** into account
- Avoid **moving objects**
- Consider **meteorological phenomena** (as constraints or additional effects on the physical model)
- Favor **air corridors** or 3D **roads**
- Add **intermediary points**
- Implement a **collaborative** aspect
- **Minimize** a given criterion like **flight time** or **fuel consumption**

Problem definition is already complex

Discrete optimization, or continious 3D Real-space

Example : obstacle avoidance



CY TECH

Grande École de sciences, d'ingénierie, d'économie et de gestion de **CY Cergy Paris Université**

FIGURE 13 – La même zone géographique sur OpenStreetMap

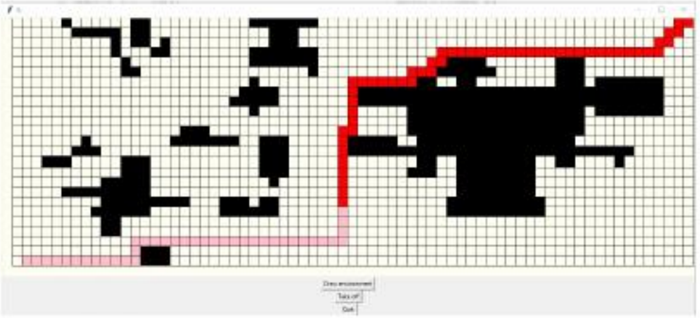
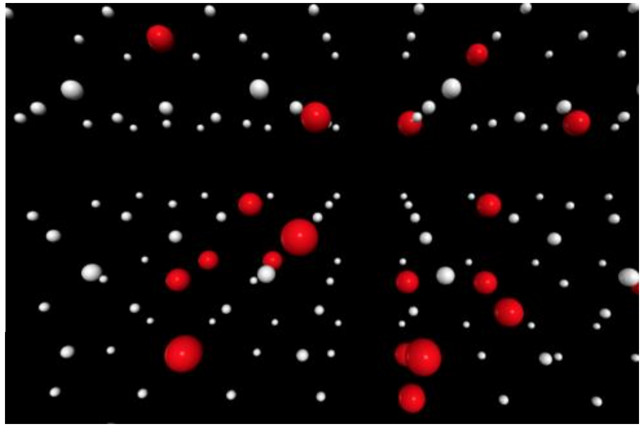
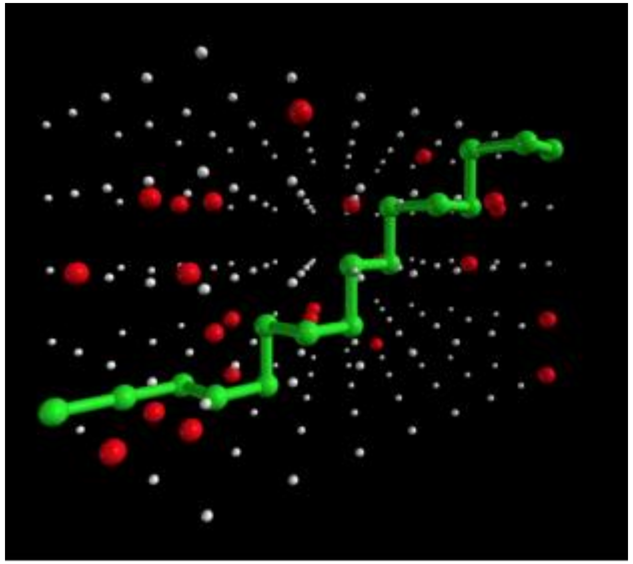


FIGURE 14 – Visualisation de l'avancée de l'aéronef





Are basic resolution enough for the problem ?

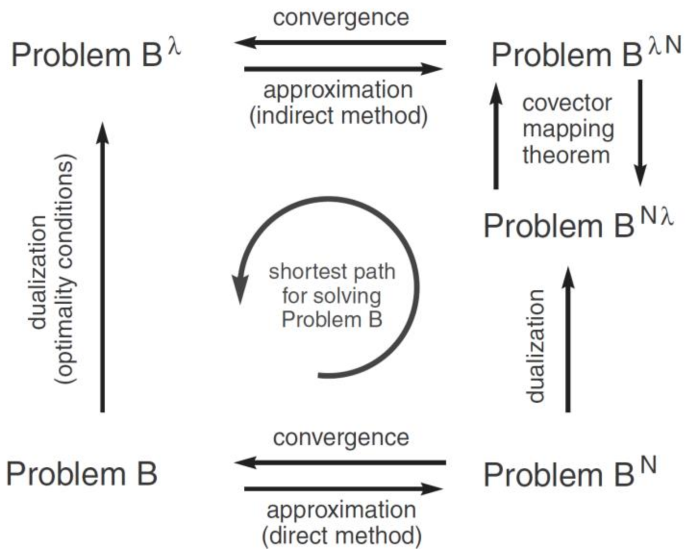
Choice of optimization method

Indirect methods

- Generalized LQR theory
  - Not applicable
- Approximate Dynamic Programming
  - No convergence proofs
  - Very complex

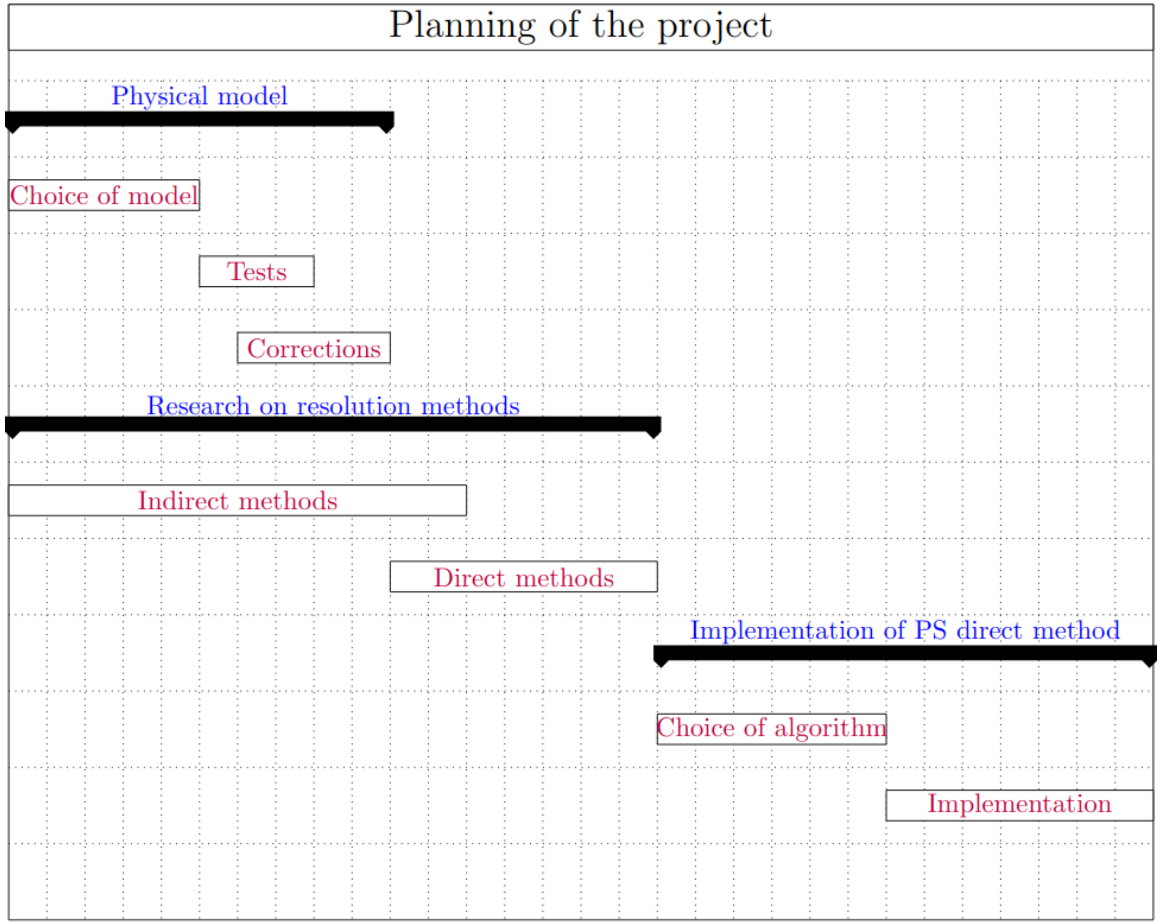
Direct methods

- Finite elements
  - Applicable
- Pseudospectral methods
  - Convergence proofs
  - Already proven



How to choose the good resolution methodology ?

Planning of the projet



Is task achieved in 5minutes or in 5 months ?

How to estimate time and ressources of the project

Data model and mathematical formulation

$$\underbrace{\begin{cases} \dot{q} = \frac{1}{2} M_s(U_\omega) q \\ \dot{x} = v \\ \dot{v} = \frac{F_a}{m} + g + \frac{U_1}{m}(k_t v + i) \\ \dot{m} = -k_t U_1 \end{cases}}$$

$$\dot{X}(t) = F(X(t), U(t)) \quad X(t) = \begin{pmatrix} q(t) \\ x(t) \\ v(t) \\ m(t) \end{pmatrix}$$

Hypothesis: the **angular velocity** is directly controlled

Position in the global coordinate system: $x(t) = (x_1(t)\ x_2(t)\ x_3(t))^T$

Speed in the global coordinate system: $v(t) = (v_1(t)\ v_2(t)\ v_3(t))^T$

F_a the **aerodynamic force**

g the **gravitational force**

m the **mass**

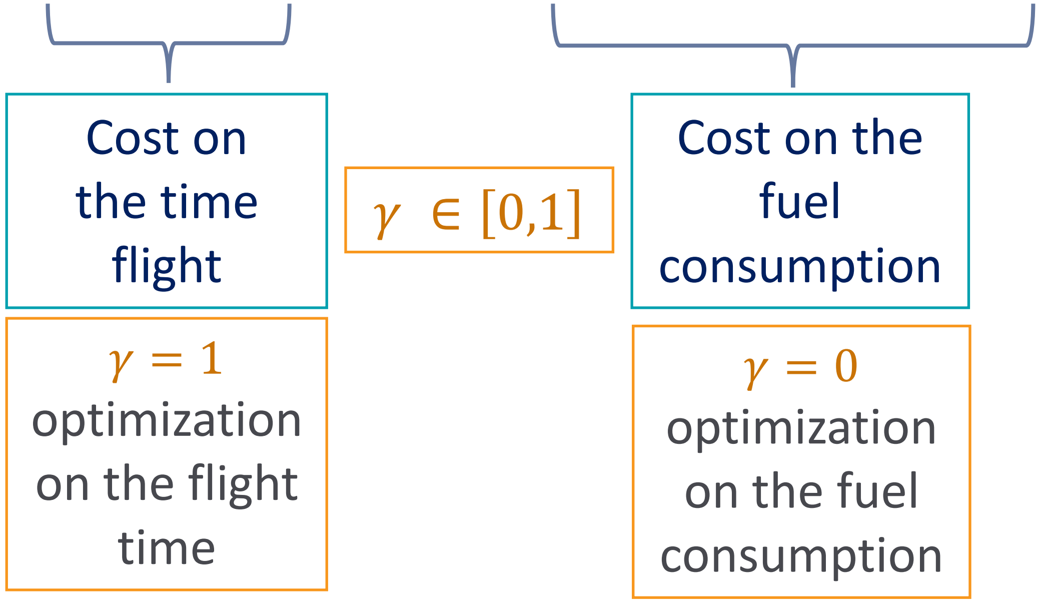
$k_t > 0$ **constant of proportionality** depending on the engine type and atmospheric values

Hypothesis: the mass derivative is proportional to the thrust

First step is to transform problem into mathematic formula

Minimize cost function – Convex optimization

$$J(X,U,t_f) = \gamma(t_f - t_0) + (1-\gamma)\int_{t_0}^{t_f} \underbrace{(k_t U_1(t))}_{\dot{m}}\, dt$$



Cost on the time flight

$\gamma = 1$ optimization on the flight time

$\gamma \in [0,1]$

Cost on the fuel consumption

$\gamma = 0$ optimization on the fuel consumption

Most IA problem can be transformed into a cost reduction optimization

Select tool

Find the solution to $\min\limits_{X,U,t_f} J(X,U,t_f)$

Minimisation of the **cost**

Subject to $\dot{X}(t) = F(X(t),U(t))$

Respect of the **physical equation**

$$\|U_i\|_\infty < U_i^{max}, \forall i \in [\![1,4]\!]$$

$$U_1(t) \geq 0, \forall t \in [t_0, t_f]$$

$$x(t_f) = x_f$$

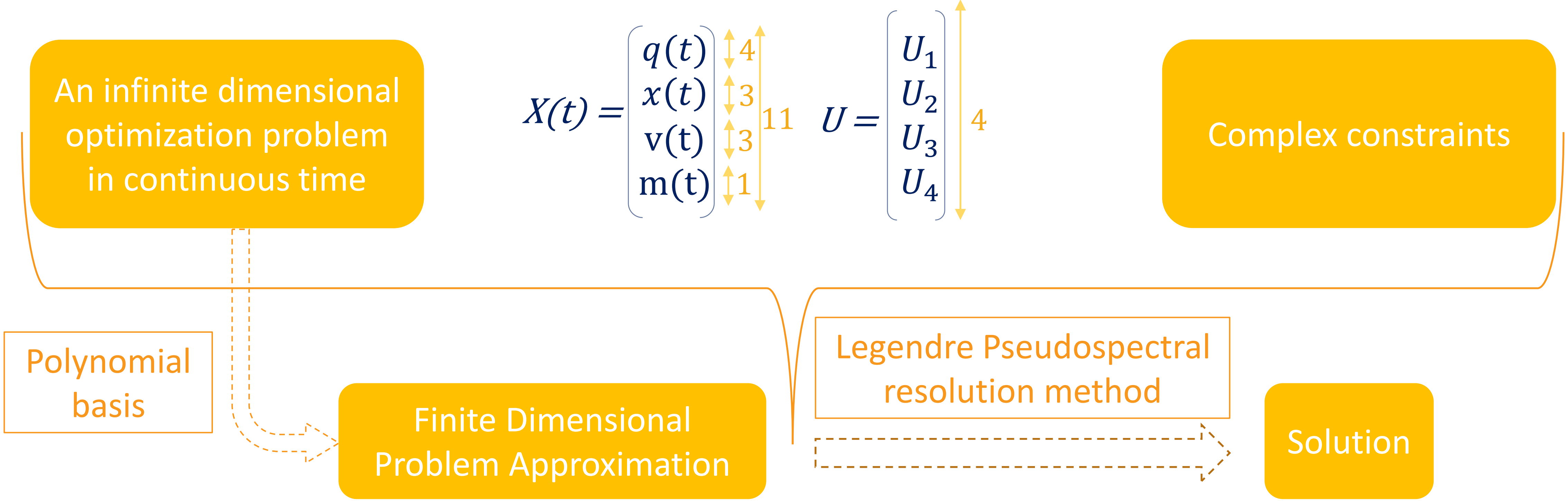
$$X(t_0) = X_0$$

$$\left\|\frac{x_1 - x_c^{1,i}}{a^i}\right\|^{p_1^i} + \left\|\frac{x_2 - x_c^{2,i}}{b^i}\right\|^{p_2^i} + \left\|\frac{x_3 - x_c^{3,i}}{c^i}\right\|^{p_3^i} \geq 1, \forall i \in [\![1, N_c]\!]$$

Respect of five **constraints** on the **cost** and the **state**

Second step is to adjust formulation to tool used to solve the expression

Resolution of the optimization problem



An infinite dimensional optimization problem in continuous time

$$X(t)=\begin{pmatrix}q(t)\\x(t)\\\mathrm{v}(t)\\\mathrm{m}(t)\end{pmatrix}\begin{matrix}4\\3\\3\\1\end{matrix}\;11 \qquad U=\begin{pmatrix}U_1\\U_2\\U_3\\U_4\end{pmatrix}\;4$$

Complex constraints

Polynomial basis

Finite Dimensional Problem Approximation

Legendre Pseudospectral resolution method

Solution

Usage of polynomials and matrix is mandatory

Legendre pseudospectral nonlinear problem

$$\dot{\hat{X}}_i\left(t_k^L\right) = f\left(\hat{X}_i\left(t_k^L\right), \hat{U}_i\left(t_k^L\right)\right)$$

Lagrange polynomials : φ_n

$$\dot{\hat{X}}_i\left(t_k^L\right) = \sum_{n=0}^{N} \hat{X}_{i,n}\, \dot{\varphi}_n\left(t_k^L\right) = \sum_{n=0}^{N} \hat{X}_{i,n}\, D_{kn}$$

$$\hat{X}_i\left(t_k^L\right) = \sum_{n=0}^{N} \hat{X}_{i,n}\, \varphi_n\left(t_k^L\right)$$

$$\hat{U}_i\left(t_k^L\right) = \sum_{n=0}^{N} \hat{U}_{i,n}\, \varphi_n\left(t_k^L\right)$$

$$D_{kn} = \dot{\varphi}_n\left(t_k^L\right)$$

$$D_{kn} = \frac{2}{t_f - t_0} \begin{cases} \dfrac{L_N(\tau_k)}{L_N(\tau_n)} \dfrac{1}{\tau_k - \tau_n}, & \text{if } k \neq n \\ -\dfrac{N(N+1)}{4}, & \text{if } k = n = 0 \\ \dfrac{N(N+1)}{4}, & \text{if } k = n = N \\ 0, & \text{otherwise} \end{cases}$$

$$\sum_{n=0}^{N} \hat{X}_{i,n}\, D_{kn} = f\left(\hat{X}_i\left(t_k^L\right), \hat{U}_i\left(t_k^L\right)\right)$$

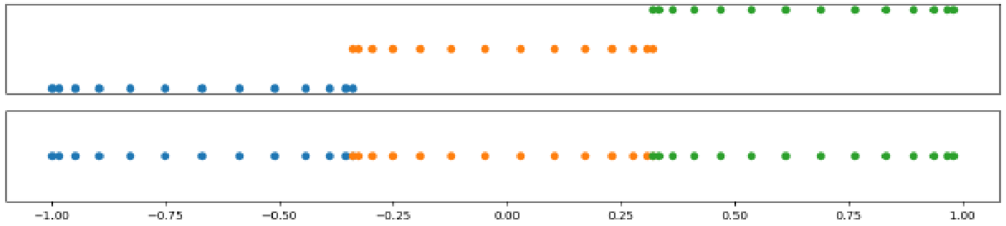


Figure 4: Legendre-Gauss-Lobato nodes for $N = 50$ (51 points) and 3 segments. The points are clumped towards points of interest (potentially non-smooth areas), and sparser in the middle of each segment (smooth area).

Example for flight path optization

Rewrited Optimization problem

Find the solution to $\min\limits_{\hat{X},\hat{U},t_f} J\left(\hat{X},\hat{U},t_f\right)$

Minimisation of the **cost**

Subject to

$$\left\|\sum_{n=0}^{N} \hat{X}_{i,n}\, D_{kn} - f\left(\hat{X}(t_k^L),\hat{U}(t_k^L)\right)_i\right\|_\infty - \delta \leq 0, \forall i \in [\![1,11]\!]$$

Respect of the **physical equation** : $\dot{X} = F(X,U)$

$$\left\|\hat{U}_i\right\|_\infty - \hat{U}_i^{max} < 0, \forall i \in [\![1,4]\!]$$

$$-\hat{U}_1(t_n^L) \leq 0, \forall n \in [0,N]$$

$$\left\|\hat{x}_i(t_N^L) - \hat{x}_f^i\right\|_\infty - \delta \leq 0, \forall i \in [\![1,11]\!]$$

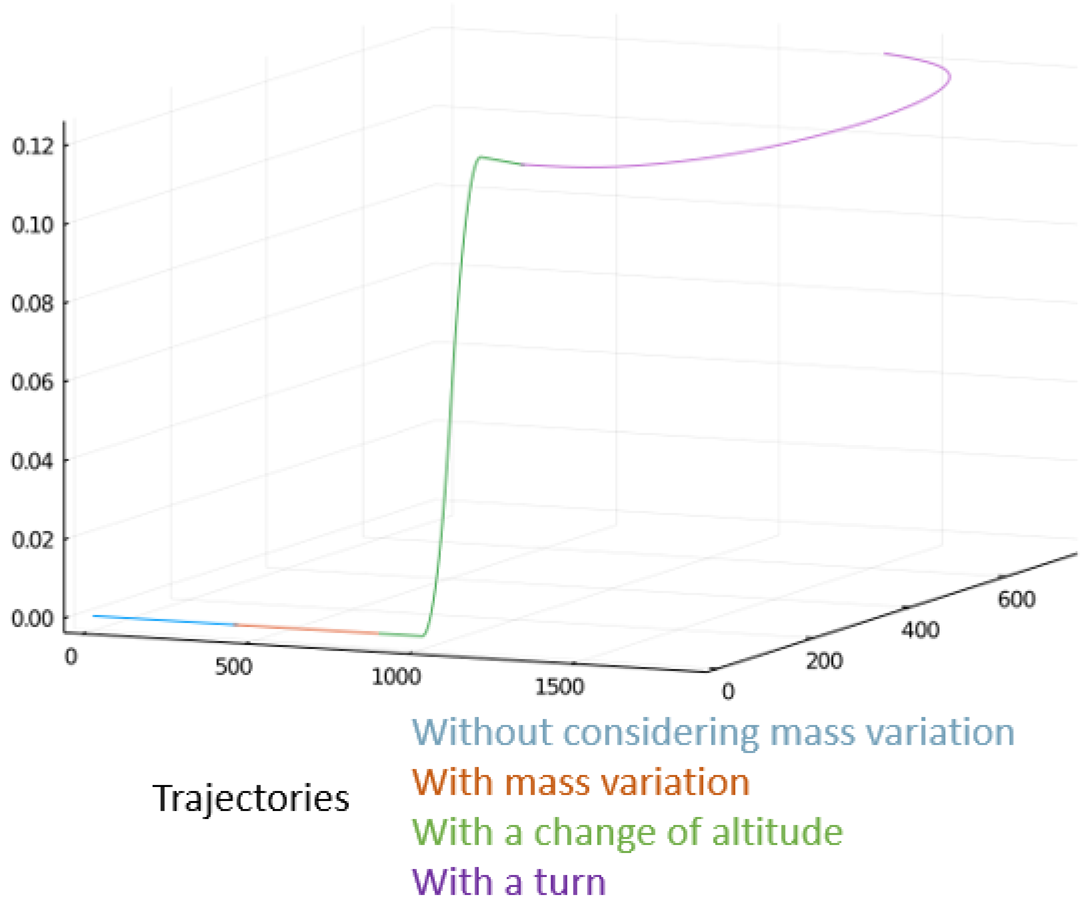
$$\left\|\hat{X}_i(t_0^L) - \hat{X}_0^i\right\|_\infty - \delta \leq 0, \forall i \in [\![1,11]\!]$$

$$1 - \left\|\frac{\hat{x}_1 - x_c^{1,i}}{a^i}\right\|^{p_1^i} - \left\|\frac{\hat{x}_2 - x_c^{2,i}}{b^i}\right\|^{p_2^i} - \left\|\frac{\hat{x}_3 - x_c^{3,i}}{c^i}\right\|^{p_3^i} \leq 0, \forall i \in [\![1,N_c]\!]$$

Respect of five **constraints** on the **cost** and the **state**

After first results, rewriting the code is always mandatory

Main difficulty : simple visualisation

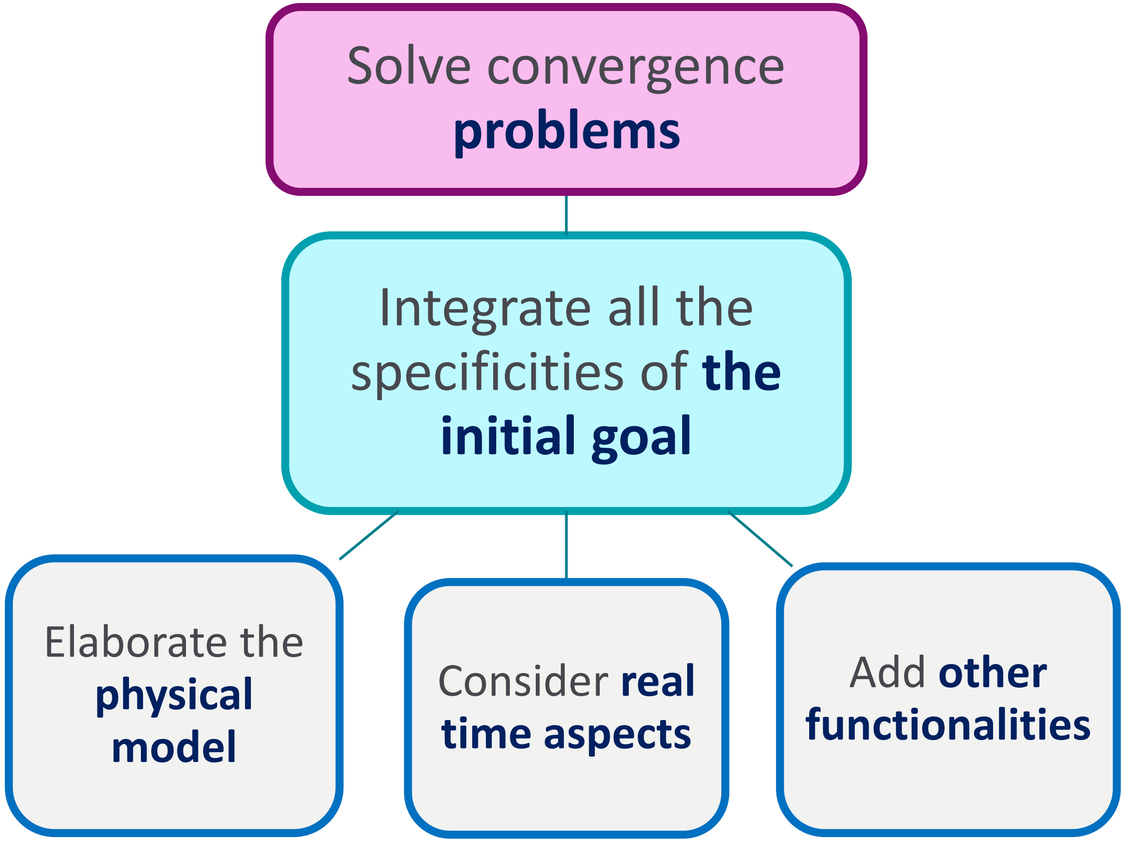


for

- Outputs integration in other applications
- Results validation before production phase
- Change management in input hypothesis

IA Project

- Mathematical resolution of the convergence problem is the first step



Solve convergence **problems**

Integrate all the specificities of **the initial goal**

Elaborate the **physical model**

Consider **real time aspects**

Add **other functionalities**

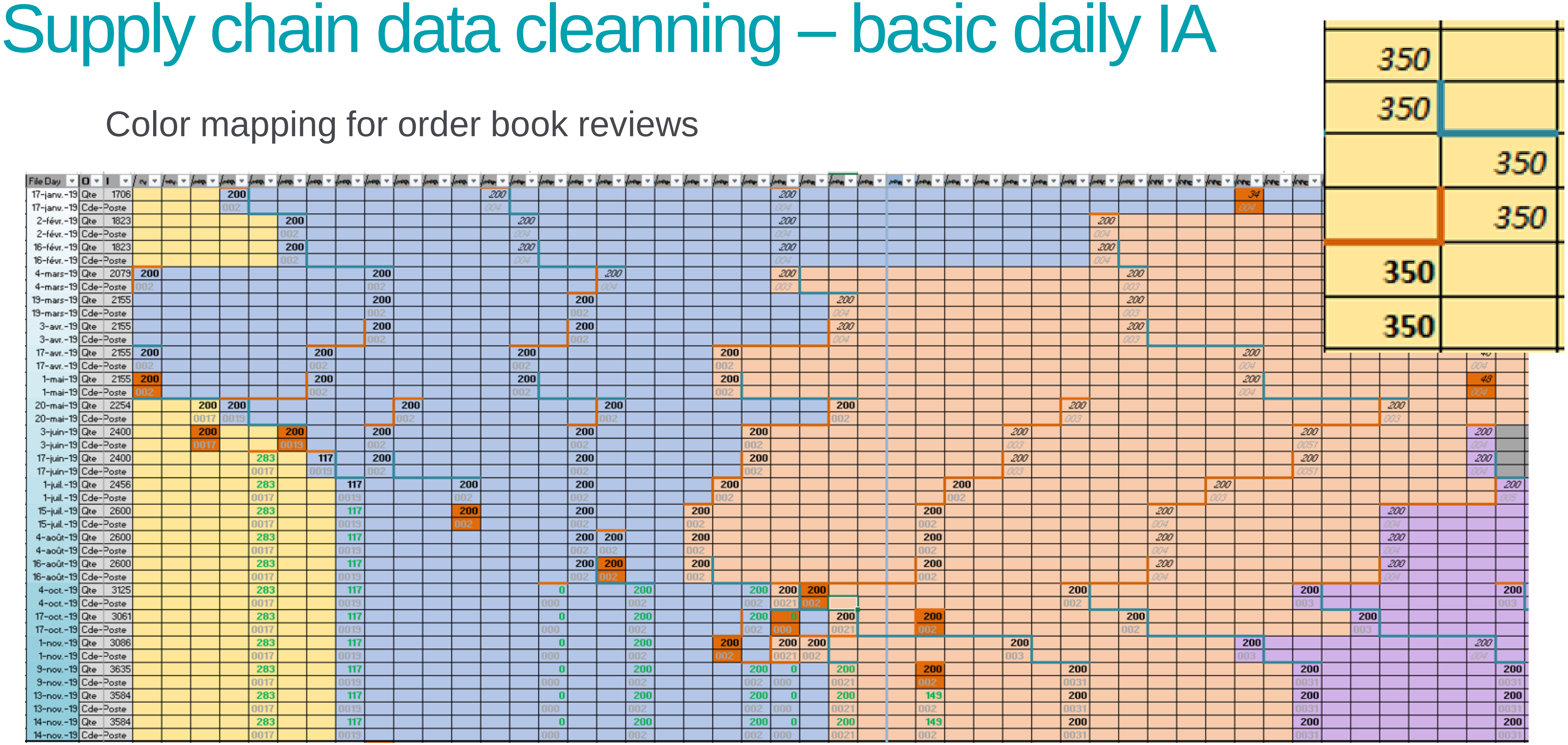
Human pilot is still mandatory :

Where to crash :

Trees or schoolyard ?

Supply chain data cleanning – basic daily IA

Color mapping for order book reviews



Within production process, Basic IA can help day to day industrial technician

Thanks

Merci

谢谢你

Xièxiè nǐ

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