Aircraft shape optimization

Focus on medium range commercial aircrafts
Agenda - Aircraft design and optimisation

- State of the art
- Aircraft mission
- Engine choice
- Aircraft hypothesis simplification
- Wings modeling
- Hybrid engines simulation
- XML model for aircraft definition
- Tail calculation
- Aircraft concept reviews
Objectives for medium range aircrafts

- Innovation in aircraft shapes
- Aerodynamic optimization
- Drag reduction and calculation
- Theory and models:
  - fuel consumption reduction and pollution
  - drag reduction
  - structural weight reduction
State of the art
#Flying1913 – Single body shape

Single wing/body at 200km/hour
#Flying1943 – After WW1 and WW2


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
Air and Space Museum in Le Bourget (FR)

- Since WW2, lots of idea have been tested
- Air museum are full of past good ideas

Materials and aeronautical technologies have improved
Ideas can be tested again and/or new concepts can emerge
Patents review

Patent databases are full of aircraft shapes
Most have more than 20 years

Patent WO9013479
Patent GB 2266873
Patent US 6070831
Aircraft design methodology review

Many methodologies for aircraft design are freely available on internet
Shape and wings optimisation


All data for mathematical optimization is available on internet.
Many advanced communication are made by research institutes

- Technical data is largely available on internet
- It is enough for aircraft modeling and optimization
Regulation and supply chain

- Difficulty is to make the complete process
- From development, prototype, tests, certification, production and maintenance
- Suppliers are very fragmented
- Final assembly lines are only 5% of aircraft value
- Engines represent 35% of total flight cost
- Passenger values is also generated on the ground and on shopping malls

Certification process is highly complex
Supply Chain production is based on small rate and high value parts
# Certification process

<table>
<thead>
<tr>
<th>Authority</th>
<th>Approval</th>
<th>Actor concerned</th>
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<tbody>
<tr>
<td>EASA</td>
<td>Part 21 J (Design)</td>
<td>TC holder / OEM</td>
</tr>
<tr>
<td>DGAC</td>
<td>OPS1</td>
<td>Operator (airline)</td>
</tr>
<tr>
<td>OSAC (Organisme pour la Sécurité de l’Aviation Civile) by delegation of the DGAC</td>
<td>Part 21 G (Production)</td>
<td>Manufacturer (OEM)</td>
</tr>
<tr>
<td></td>
<td>Part 145 (Maintenance)</td>
<td>Repair shop (MRO)</td>
</tr>
<tr>
<td></td>
<td>Part M/G (Continuing Airworthiness)</td>
<td>Airworthiness organization (CAMO)</td>
</tr>
<tr>
<td></td>
<td>Part 147 (Training)</td>
<td>Training organization</td>
</tr>
</tbody>
</table>

A long term approach is mandatory, for an aircraft manufacturer.
State owned organizations are supporting research and certification phases.
All repair processes have to be defined during certification

Maintenance review board

All repair processes are included within IPC and OEM documentation

MRB Actors

Maintenance Working Group (MWG)
- Authorities
- TC HOLDER
- OPERATORS - chairman

Propose minimal maintenance tasks to the ISC
Perform the maintenance technical analysis

Industry Steering Committee (ISC)
- Authorities
- TC HOLDER - chairman
- OPERATORS

Validate the maintenance tasks and drive MWG work
Direct the maintenance program
Define the working principle

Maintenance Review Board (MRB)
- Authorities

Validate the maintenance program proposed by the ISC
Elaborates the MSBR

Authority policy

MRBR

MSG-3 analysis
PPH
MPP

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Even today, aircraft and engines development is still hazardous for large players.
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 consumption

What is the value for passengers, where is the added-value?
Most studies are made on exotic shapes
Most aircrafts are delivered within regional and single aisle categories
20-Year Market Demand

<table>
<thead>
<tr>
<th>Region</th>
<th>Deliveries</th>
<th>2040 Total Fleet</th>
<th>Services Market Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>9,160</td>
<td>2040 Total Fleet: 10,846</td>
<td>Services Market Value: $2.27TB</td>
</tr>
<tr>
<td>Europe</td>
<td>8,705</td>
<td>2040 Total Fleet: 4,510</td>
<td>Services Market Value: $1.34TB</td>
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<tr>
<td>Russia and Central Asia</td>
<td>1,540</td>
<td>2040 Total Fleet: 2,090</td>
<td>Services Market Value: $1.16TB</td>
</tr>
<tr>
<td>Latin America</td>
<td>2,530</td>
<td>2040 Total Fleet: 3,020</td>
<td>Services Market Value: $605B</td>
</tr>
<tr>
<td>Africa</td>
<td>1,030</td>
<td>2040 Total Fleet: 1,130</td>
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<tr>
<td>Middle East</td>
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<td>2040 Total Fleet: 1,530</td>
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<tr>
<td>Asia-Pacific</td>
<td>8,945</td>
<td>2040 Total Fleet: 10,520</td>
<td>Services Market Value: $1.94TB</td>
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<tr>
<td>China</td>
<td>8,700</td>
<td>2040 Total Fleet: 6,350</td>
<td>Services Market Value: $3.60TB</td>
</tr>
</tbody>
</table>

**Forecast shares of traffic growth, by flow**

- Intra-China: 17%
- Asian Regional: 12%
- Intra-Europe: 9%
- Intra-North America: 8%
- Other Intra-Region Traffic: 9%
- Other Traffic Flows: 45%

- >1/4 of commercial aircraft deliveries are planned in Asia
- 75% on single aisle
Aircraft mission
Once mission is defined, aircraft design is only driven by technical parameter optimization.
Overall passenger process optimization

- Total cost of ownership should take into account airports and congestions
Airport congestion

Example: Number of movements per hour on a regional airport

Objective
4 hours door to door
Anywhere in Europe

- Airport congestion and landing planning is already an issue
- Airport are not scaleable
Turn around time and Refueling

Refueling is on the turn-around critical path at the airport
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)
Objectives for aircraft design

Needs

- Study of aeronautical configuration
- Choice of optimal configuration
- Establishment of a quick decision tool and methodology

Objectives

- Configuration proposal
- Parametrical optimization
- Modular program

Multi fonctionnal optimization is necessary, leaving small space to innovative solution
First step

Engine choice

TRL1 and TRL2
Flight simulation

- $\vec{P}$: Gravity force;
- $\vec{R}_N$: Support force (from the ground);
- $\vec{F}_f$: Friction force (on the wheels);
- $\vec{R}_x$: Air drag;
- $\vec{T}$: Thrust (from the engines);

So we have

$$\sum \vec{F} = \vec{P} + \vec{R}_N + \vec{F}_f + \vec{R}_x + \vec{T}$$

**Bernoulli theory:**

$$P_e + \frac{\rho \cdot V_e^2}{2} + z_e = P_0 + \frac{\rho \cdot V_0^2}{2} + z_0 + \rho g \cdot H_{ET}$$

Substituting every force with the results found, the equation (1) becomes

$$m \frac{dV_0}{dt} = -C_x \frac{\rho \cdot V_0^2}{2} + N \cdot T$$

Engine choice need basic mathematics and model
Aircraft and engine simulation

Basic models are sufficient for engine choice

Results III.1: Speed of the plane during take-off. The engines have an efficiency of 65% and the plane weight 100 t.

Results III.2: Speed of the plane during take-off. The plane has 2 TP400 with an efficiency of 85%.

Results III.3: Speed of the plane during take-off. The plane has 2 TP400 and weight 100t.

Results III.4: Speed of the plane during take-off. The plane has 2 CFM56-5B and weight 100 t.
Engine failure during takeoff phases

Results V.1: Angle of the plane with a flap 50%, 100%, and 150%, and a wing area of 180 m² and an initial wing angle of 3°

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

Model have to take into account acceleration phase during take-off and first minutes of flights with engine failure.
### Engine choice

<table>
<thead>
<tr>
<th>Application</th>
<th>SAM146</th>
<th>CFM56-3C1</th>
<th>CFM56-3B2</th>
<th>CFM56-3B1</th>
<th>V2522-A5</th>
<th>CFM56-5A5</th>
<th>CFM56-5B6</th>
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<tr>
<td>lb</td>
<td>3350</td>
<td>4301</td>
<td>4301</td>
<td>4290</td>
<td>5210</td>
<td>4995</td>
<td>5250</td>
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<tr>
<td>kg</td>
<td>1519,225</td>
<td>1950,50</td>
<td>1950,50</td>
<td>1945,52</td>
<td>2362,74</td>
<td>2265,23</td>
<td>2380,88</td>
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<td><strong>Poussée Max</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>23500</td>
<td>22000</td>
<td>20000</td>
<td>23000</td>
<td>23500</td>
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<td>N</td>
<td>71612,8</td>
<td>104528</td>
<td>97856</td>
<td>88960</td>
<td>102304</td>
<td>104528</td>
<td>104528</td>
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<tr>
<td><strong>Diamètre</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in</td>
<td>48,2</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>63,5</td>
<td>72</td>
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<tr>
<td>m</td>
<td>1,22</td>
<td>1,60</td>
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<td>1,61</td>
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<td><strong>Longueur</strong></td>
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<td>93,1</td>
<td>93,1</td>
<td>126</td>
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<td>m</td>
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<td>2,36</td>
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<td>2,36</td>
<td>3,20</td>
<td>2,51</td>
<td>2,60</td>
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<td><strong>BPR</strong></td>
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<td></td>
<td>4,43</td>
<td>6</td>
<td>5,9</td>
<td>6</td>
<td>4,9</td>
<td>6,2</td>
<td>5,9</td>
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<tr>
<td><strong>SFC_sea level</strong></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>lb/(lbf.h)</td>
<td>0,370</td>
<td>0,396</td>
<td>0,396</td>
<td>0,386</td>
<td>0,340</td>
<td>0,3316</td>
<td>0,3276</td>
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<tr>
<td>kg/(daN.h)</td>
<td>0,377</td>
<td>0,404</td>
<td>0,404</td>
<td>0,394</td>
<td>0,347</td>
<td>0,338</td>
<td>0,334</td>
</tr>
</tbody>
</table>

List of available engines per aircraft size is limited.
Engines modeling

Engine performance and consumption can be modeled with limited number of internal parameters.
**Consumption simulation**

Basic flight consumption and range can be estimated with good precision.

Speed is one of the most critical parameter.

### Consumption en croisière

<table>
<thead>
<tr>
<th>Vars</th>
<th>Mach 0.7</th>
<th>Mach 0.5</th>
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<tbody>
<tr>
<td>Cz</td>
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<td>0,86961957</td>
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<tr>
<td>Cx</td>
<td>0,027943805</td>
<td>0,050191659</td>
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<tr>
<td>Rx=Fn nav(20)</td>
<td>54447,8 N</td>
<td>49896,5 N</td>
</tr>
<tr>
<td>Fn ref(20)</td>
<td>4625,5 N</td>
<td>5331,2 N</td>
</tr>
<tr>
<td>Fn ref(20)*Ps/0/Ps</td>
<td>10065,4 N</td>
<td>11601,0 N</td>
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<tr>
<td>Cs/racine(teta)</td>
<td>1,36 Kg/daN/H</td>
<td>1,4 Kg/daN/H</td>
</tr>
<tr>
<td>teta</td>
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<td>0,862248439</td>
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<tr>
<td>Cs</td>
<td>1,26 Kg/daN/H</td>
<td>1,30 Kg/daN/H</td>
</tr>
<tr>
<td>Ct</td>
<td>114,60 Kg/min</td>
<td>108,11 Kg/min</td>
</tr>
<tr>
<td>Ck</td>
<td>8,63 Kg/km</td>
<td>11,40 Kg/km</td>
</tr>
</tbody>
</table>

### Distance franchissable

<table>
<thead>
<tr>
<th>Vars</th>
<th>Mach 0.7</th>
<th>Mach 0.5</th>
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</thead>
<tbody>
<tr>
<td>m0</td>
<td>98750 kg</td>
<td>98750 kg</td>
</tr>
<tr>
<td>m1</td>
<td>77500 kg</td>
<td>77500 kg</td>
</tr>
<tr>
<td>masse moyenne</td>
<td>88125 kg</td>
<td>88125 kg</td>
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<tr>
<td>f</td>
<td>15,87770365</td>
<td>17,32597766</td>
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<td>distance</td>
<td>2473,03 km</td>
<td>1872,50 km</td>
</tr>
<tr>
<td>temps de vol</td>
<td>3,09 h</td>
<td>3,28 h</td>
</tr>
</tbody>
</table>
Propeller modeling

Modeling of a turbofan or turbopropeller is highly complex. But main information for aircraft design can be simplified by flight phases.
Aircraft design hypothesis
TRL1 and TRL2
Wing simplification

Wings can be simplified by flight phases (flaps in / out) and wings can be simulated with basic shapes.
Most of efforts are taken to the structure by skin effect
Easy way to estimate structure weight of a complete aircraft
Landing gear simplification

Basic forces lead to a generic landing gear shape. Estimated weight is achieved with low level of error.
Aircraft design parameters simplification

Aircraft TRL1 design can be achieved with limited number of parameters, and compared to other aircrafts and engines choice.
Basic aircraft flight simulation

Multi form aircraft simulation does not need IA
Drag calculation : A320

- All shapes of regular aircrafts are mostly available and can be implemented within air flow software
- Error margin in calculated values can be estimated compared to existing aircrafts
### Propeller and blades

<table>
<thead>
<tr>
<th></th>
<th>ATR72-500</th>
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<tbody>
<tr>
<td><strong>Rendement Hélice</strong></td>
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</tr>
<tr>
<td><strong>CAS flap 15° pour 22,5t</strong></td>
<td></td>
</tr>
<tr>
<td>$kt$</td>
<td>101,125</td>
</tr>
<tr>
<td>$mph$</td>
<td>116,372572</td>
</tr>
<tr>
<td><strong>V2</strong></td>
<td></td>
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<tr>
<td>$kt$</td>
<td>114,27125</td>
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<tr>
<td>$mph$</td>
<td>131,501006</td>
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<tr>
<td>$m/s$</td>
<td>58,781131</td>
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<td><strong>Poussée Totale</strong></td>
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<td>$lbf$</td>
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<td>$N$</td>
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<tr>
<td><strong>Poussée par Moteur</strong></td>
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<tr>
<td>$lbf$</td>
<td>112</td>
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<tr>
<td>$N$</td>
<td>25124</td>
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</tbody>
</table>

- Propellers and blades are critical for engines modeling.
- They can be simplified with basic parameters.

During early design phases basic engines and flight information are sufficient.
• Noise reduction is a level 2 step compared to consumption and weight optimization
• Engine choice is made first, then fuselage and wing are choosen
• then implement noise optimization that will contribute positively or negatively to consumption level
Today medium range shape consensus

- Twin engines (fuel)
- 2 Pilots
- Stabilizer at the back
- Low wing, near gravity center
- Round fuselage
- Passenger on top of fret
- Tricycle landing gear

Main market and technical driver on single aisle aircrafts confirm regular shape choice. There is today an optimum for twin engines aircraft design, progress are incrementals.
Wing design
High aspect ratio

- Fuel reduction are made with engines optimization then with wings shape.
- High aspect ratio wings are one solution (increase width until material and logistic constrains).
Wing shape

Hypothesis:
• Aircraft are using vertical air forces to balance weight
• Compromise between take-off and cruise flight
• Aircraft design is made according to crash condition

Aerodynamic parameters can be easily calculated
Choice of NACA profile is driven by flight optimization during cruise and take-off phases.
Automation of wing design and simulation

Automated parametric shape of wings that generates a complete wing design
Parametric optimization can be integrated within automated simulation

Wing design and simulation is now easy and rapidly simulated during early stage development phases
Modal analysis is made at early stage of developments
Integrated modeling software

Quick model with basic air flow description can be implemented to obtain quick basic results with high level of accuracy.
Advanced simulation

Aeroacoustic Simulation Delivers Breakthroughs in Aircraft Noise Reduction

Aircraft manufacturers face increasingly stringent standards for reducing community noise. Conventional aircraft development methods based on engineering experience, test-draws and flight testing will not suffice to meet future noise reduction targets. Computational Fluid Dynamics (CFD) software based on so-called Reynolds-averaged Navier-Stokes (RANS) methods has revolutionized aerodynamics engineering, but is insufficient for high-fidelity aeroacoustic simulation. Moreover, the Leibniz-Dortmund-based technology of Dassault’s Fluent software provides aeroacoustic simulation accuracy comparable to wind tunnels and flight testing.

Advanced software exits and can be used very precisely for drag simulation and noise estimation
Topological wing optimization

Basic optimization IA is already implemented within design software

**But** IA integration within aircraft design is difficult due to multicriteria optimization

Multifunctional design is mandatory (structure, aerodynamic, equipment)
Variable geometry wings

Variable wings geometry can be simulated with basic technical parameters by flight phases
Morphing wings

Flaps are already a basic morphing wing With optimums: cruise, take-off and climb, landing

Reliability is key to assure high availability and reliability

Maintenance issues have to be overtaken

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

https://sites.google.com/site/citcolmar/etude-experimentale-d-un-profil-d-aile-d-avion-a-cambrure-variable
Hybrid engines
Flight phases

Calcul des performances:

<table>
<thead>
<tr>
<th></th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
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<td>260</td>
<td>175</td>
<td>117</td>
<td>117</td>
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<tr>
<td>Consommation horaire de carburant (kg/h)</td>
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<td>12638</td>
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<td>645</td>
<td>1613</td>
<td>2h40</td>
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<tr>
<td>Consommation (kg)</td>
<td>246</td>
<td>2264</td>
<td>4299</td>
<td>4082</td>
</tr>
<tr>
<td>Longueur (km)</td>
<td>2</td>
<td>74,9</td>
<td>275</td>
<td>1645</td>
</tr>
</tbody>
</table>

Take-off is critical in aircraft design
Including engine failure
Except for cruise flight, most of fuel consumption is made during first flight segments
Engines simulation

Complex aircraft modeling does not need IA (eg. hybrid engines)
Turbofan used only for take-off

Example of an hybrid aircraft twin propeller + 1 small turbofan for takeoff
Hybrid engines aircraft: 2 turboproellers + 1 turbofan

Maximal constrain is engine failure during take-off
XML aircraft model
Figure 5 - XML Architecture
Basic xml language is sufficient to launch multi-form parametric optimization
Engine simulation

Simulation are better when all engines stages are taken into accounts
A321 simulation

Figure 13 - Data of a cruise flight of an A321
Wing shape for aircraft concepts

High level of accuracy is already achieved with basic modular description (e.g. fuselage = rocket shape)

Every aircraft shape can be easily transformed into parametric equation
Tail calculation
Tail design

Many design are possible
Horizontal and vertical stabilizer have a better stability at the back
Tail calculation

Stabilizing forces can be estimated with basic wing shape
Engine Failure

Some design are impossible:
Engines have to be near center of gravity and lift

Engine failure is still a major constrain for tail shape
Automation of simulation

All calculation parameters can be automated, to study different shapes and flight conditions.

Multiple step optimization can be achieve with calculation automation and shape parametric optimization
Landing gear
Green taxiing system

On the ground robots are a good solution for taxiing operation
Landing gear shape

Landing gears can be simulated with basic parametric description
Landing gear width

Width between legs of the main landing gear is already a constrain for large airplanes (turns)
Landing gear noise

Landing noises are also generated by landing gear. Fixed main landing gears can be a solution.
Equipements
APU choice

APU choice is made according to passenger capacity and mission definition.
APU plays a bigger rôle for electric and air generation.
Electric energy management has an increasing role.
Lines of codes become significant. Software needs to be certified. Life of an aircraft is much longer than individual electronics parts.
Engine nacelle + reverse

A310

B737 max

Nacelle optimization allows noise and consumption optimization.
Reverse are mandatory during landing slow down.
Cruise flight optimization

Major parameters are wet surface, frontal surface, rear cone shape, front angular shape
Fuselage optimization and shape

Choice of fuselage is main on mission constrains
Multi-bubble fuselage

Today, medium range aircrafts have passengers on top of fret
Multibubble fuselage are possible (but exact same diameters for each bubble)
Skin optimization

Aircraft windows

Rivet suppression

Whatever shape, first optimization to achieve is skin drag reduction
Concept reviews
Advantages and drawbacks
Hypersonic aircrafts

Advantages:
- High speed
- Travel time reduction
- High altitude

Drawbacks:
- Costs, noise
- Avoidance capacity
- Limited capacity
- Limited market

Source: ZEHST de EADS
Rhomboedrical wings

Advantages
• Reduced drag

Drawbacks
• Flight stability
• Structural conception
• On the ground access
• Weight regarding efficiency
Multi bubble fuselage

Advantages
- Capacity
- Reduced length

Drawbacks
- Structural design
- Drag at high speed

Source NASA/MIT
Flying wings

Advantages:
- Reduced drag
- Cabin width
- Large capacity

Drawbacks:
- Large wing
- Large landing gear (width)
- Structural weight
- Passenger disembark time

Source: X-48 (NASA)
Source: Clip-Air (EPFL)
Transport aircraft with vertical take-off and hybrid power

Smallest aircraft that can handle a 20 feet container is an Hercules 130

Weight of a 20' container of 12t is the same as 140 passengers
Urban air mobility – Hybrid solution

More than 150 projects in the world
For the next General Aviation revolution
Electrical aircrafts

Advantages
• Reduced costs of engines
• Autonomy (wire, solar)
• Acceleration and high control
• Reduced pollution during flight

Drawbacks
• Battery autonomy / Energy storage
• Battery weight (in cruise)
• Lake of average power

Electric aviation is directly linked to battery power
Thanks
Merci
谢谢你
Xièxiè nǐ