Conceptual design of Blended Wing Body aircraft

Jean-Yves Trépanier
Martin Weil Brenner

National Colloquium on Sustainable Aviation 2013
University of Toronto Institute for Aerospace Studies (UTIAS)
May 15-16, 2013

CHAIRE IDEA CHAIR

NSERC/J.A.Bombardier/Pratt&Whitney Canada
Industrial Research Chair in
Integrated Design towards Efficient Aircrafts

POLYTECHNIQUE MONTRÉAL

BOMBARDIER

Pratt & Whitney Canada
Une société de United Technologies

FONDATION J. ARMAND BOMBARDIER

CRSNG NSERC

Agenda

- Introduction
- BWB design method
  - Analysis tools
- Design Optimization
- Concluding remarks and future work

CHAIRE IDEA CHAIR

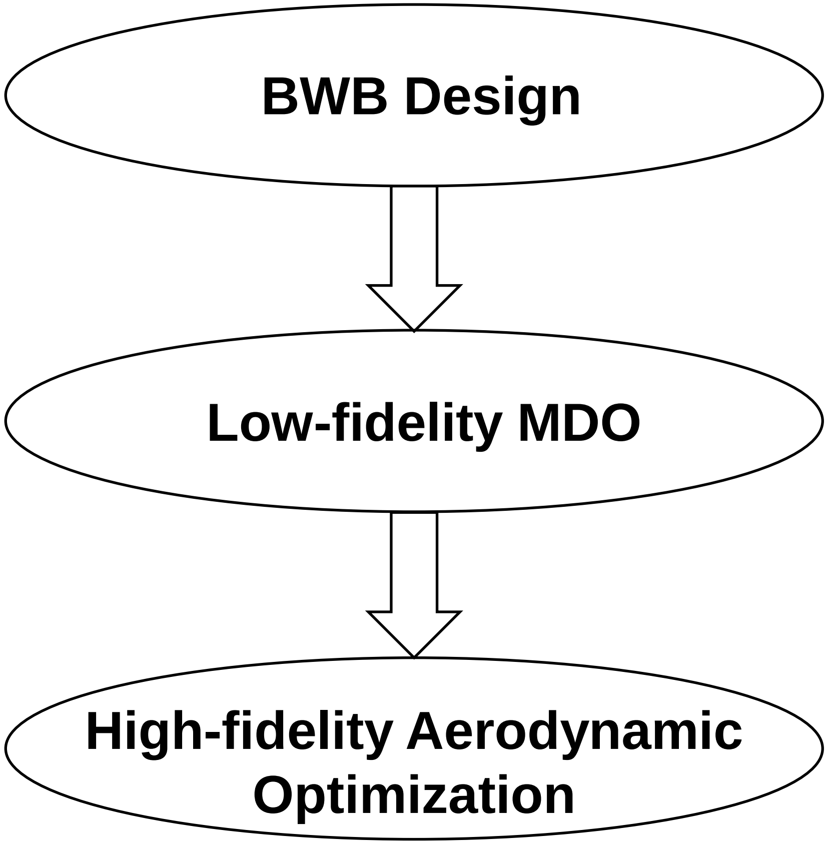
The Blended Wing Body aircraft

Potential 25% reduction in fuel burn

Many challenges in aerodynamic design

CHAIRE
IDEA
CHAIR

Aerodynamic and MDO Design Strategy



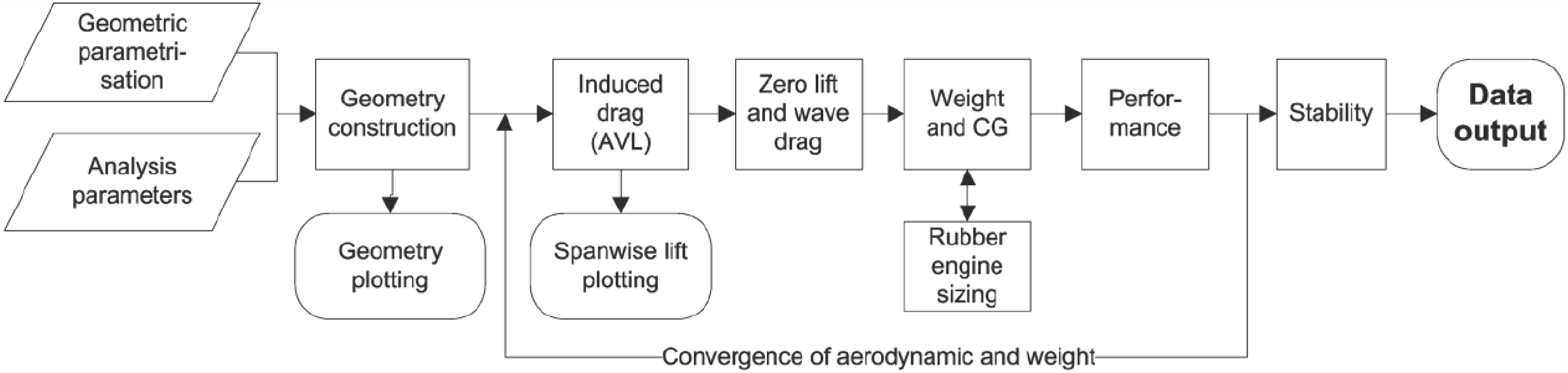
Very flexible user-based tool to generate a first BWB configuration for a given set of requirements

Automatic optimization of planform based on low-fidelity analysis tools

Design of airfoil sections to meet performance and constraints target

BWB design – Global algorithm

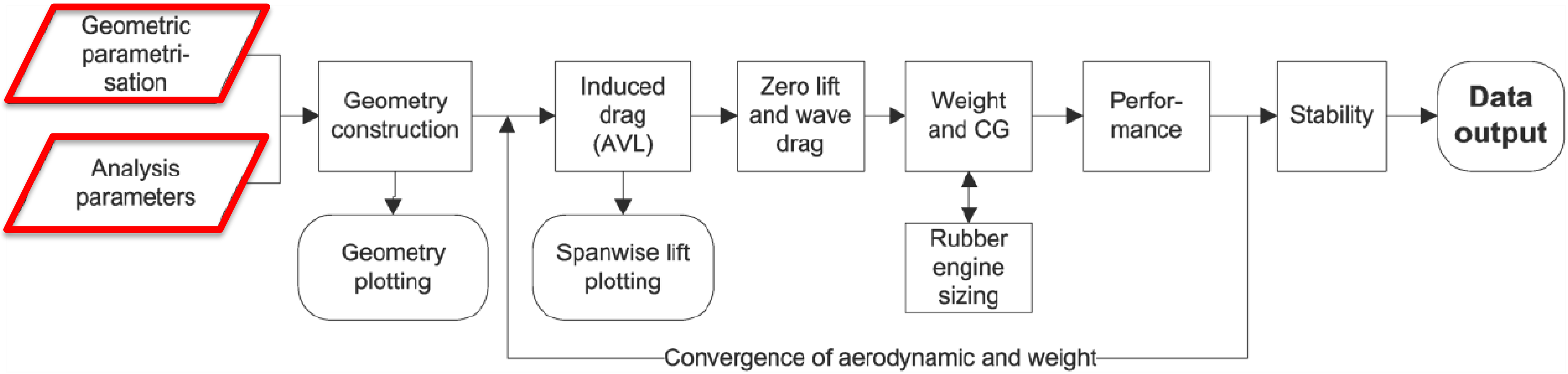
The BWB is characterized by a strong coupling between shape, aerodynamics, weight and stability.



The designer can rapidly play with the geometry and get the main impact on aircraft characteristics

CHAIRE IDEA CHAIR

BWB design – Global algorithm



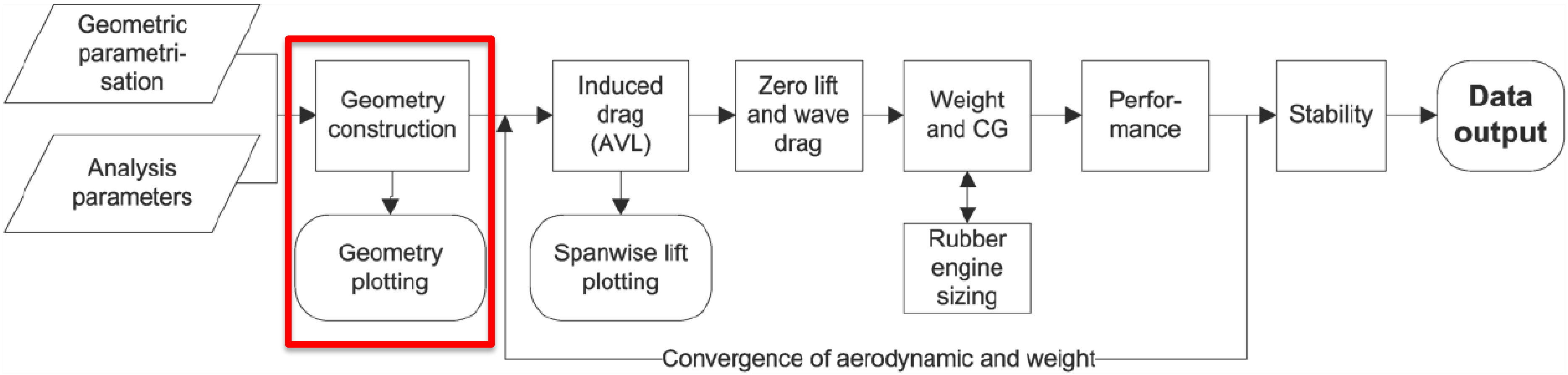
Geometric Parameters

- **Planform**
- **Airfoils**

Analysis Parameters

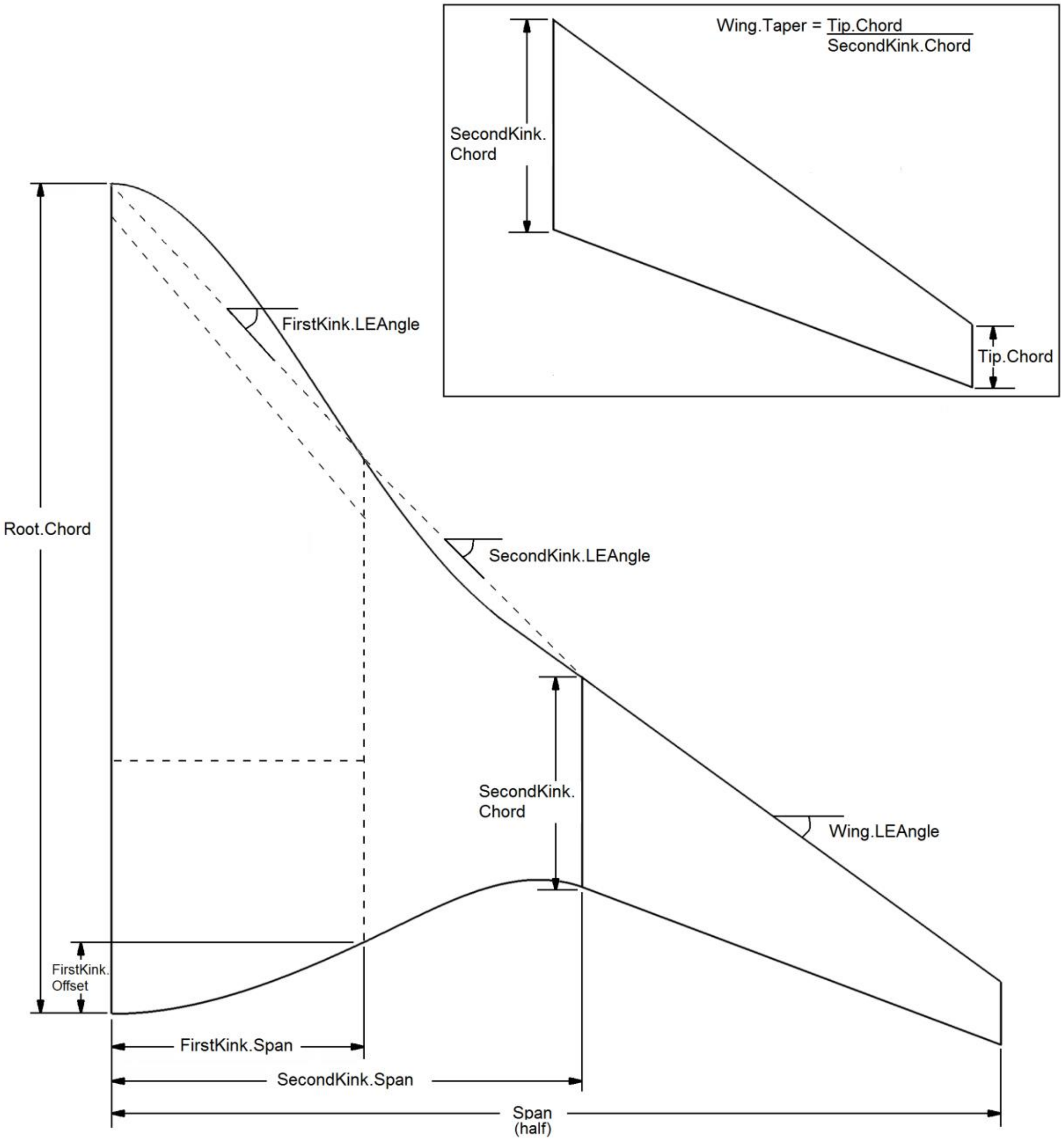
- **Range**
- **Cruise speed**
- **Altitude**

BWB design – Global algorithm



CHAIRE IDEA CHAIR

BWB design – Planform parameterization



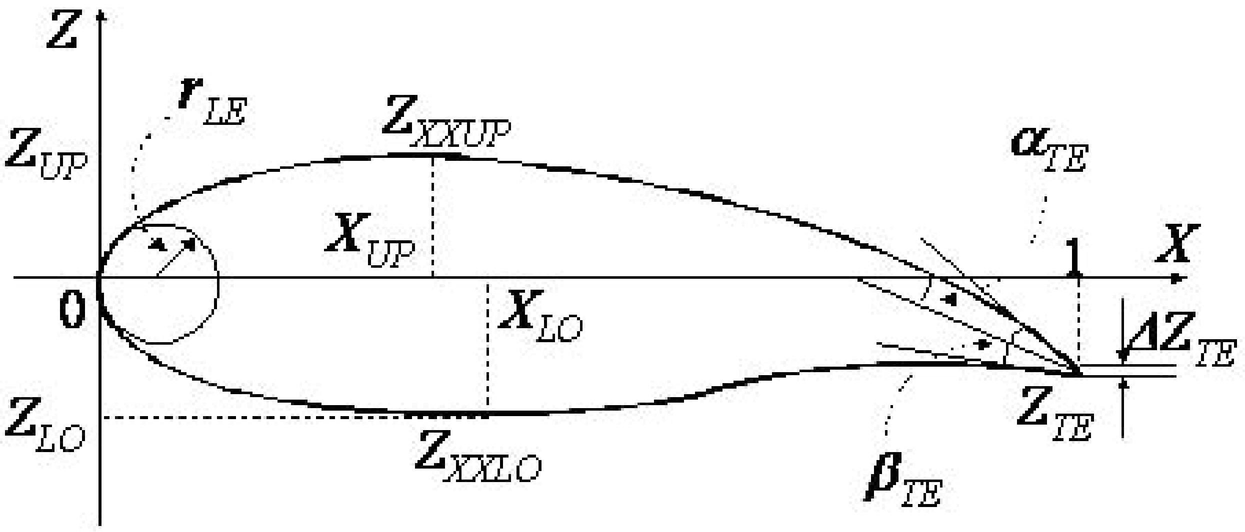
- **10 parameters**

  Root.Chord
  FirstKink.Span
  SecondKink.Span
  Span
  FirstKink.Offset
  SecondKink.Chord.
  Wing.Taper.
  FirstKink.LEAngle
  SecondKink.LEAngle
  Wing.LEAngle

- **Spline Interpolation used to define LE and TE smooth curves**

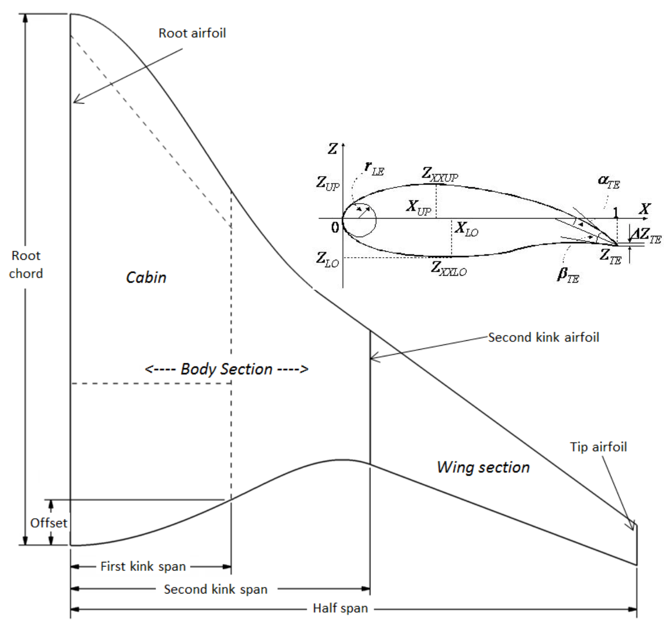
BWB design – Airfoil parameterization

- Airfoil parameterization : PARSEC method
  - 10 parameters per section
  - Intuitive parameters
  - Allow representation of most airfoil section

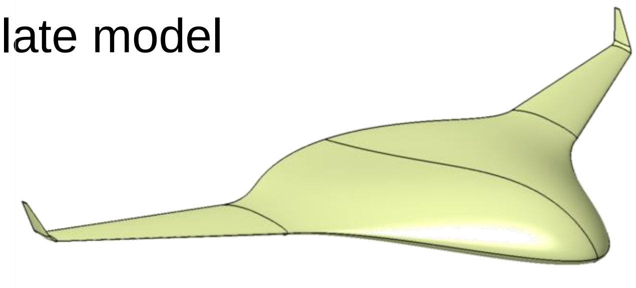


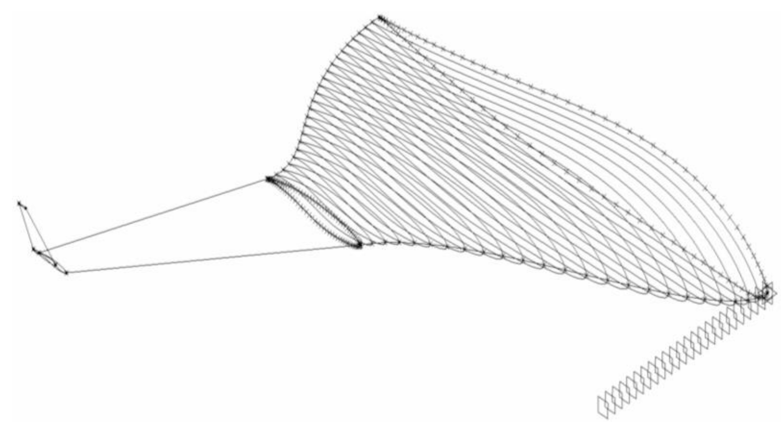
Transfer to CATIA

- **Controlled within Matlab**
  - Capri driveMM is used to update a template model



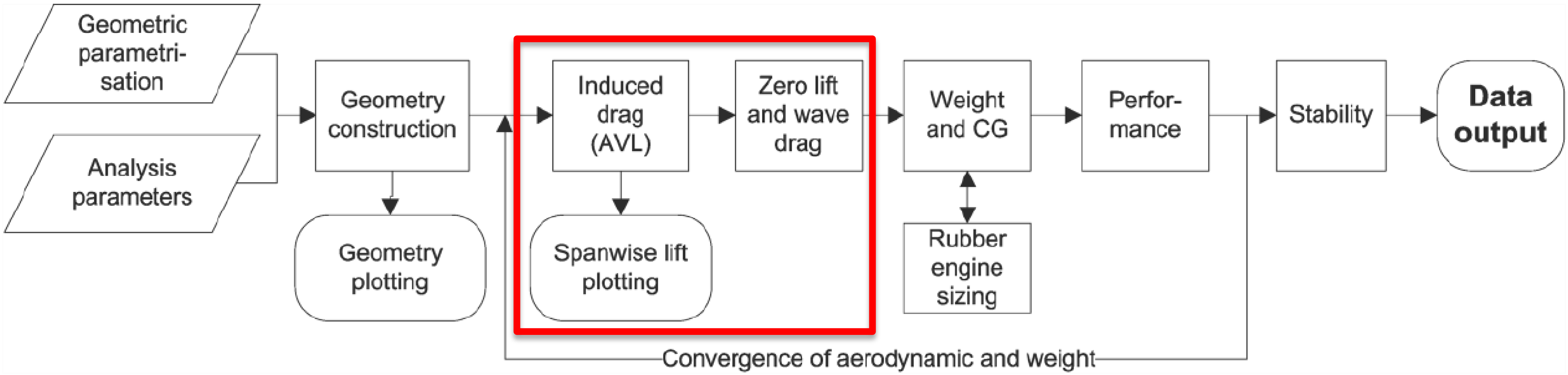
Geometric parameters





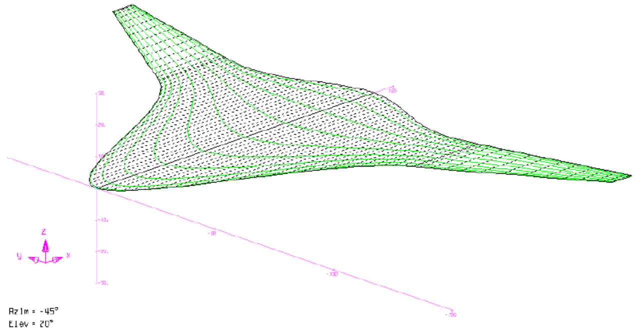
Over 1000 points, lines and surface definition depending on desired resolution

BWB design – Global algorithm

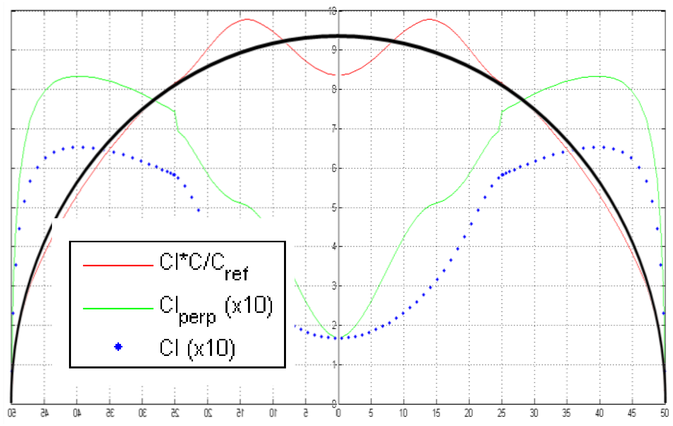


BWB design – Induced Drag

- Empirical method not applicable to Blended Wing Body
- Simple numerical simulation based on vortex lattice method
  - Calculation performed in AVL
- AVL
  - Written by Harold Youngren and Mark Drela
  - Lift calculated with airfoil camber
  - Section thickness correction
  - Prandtl-Glauert correction for compressibility
  - Output lift distribution and induced drag coefficient



$$C_{D_i} = \frac{C_L^2}{\pi A e}$$



Spanwise Wing Loading

CHAIRE IDEA CHAIR

BWB design – Zero Lift Drag

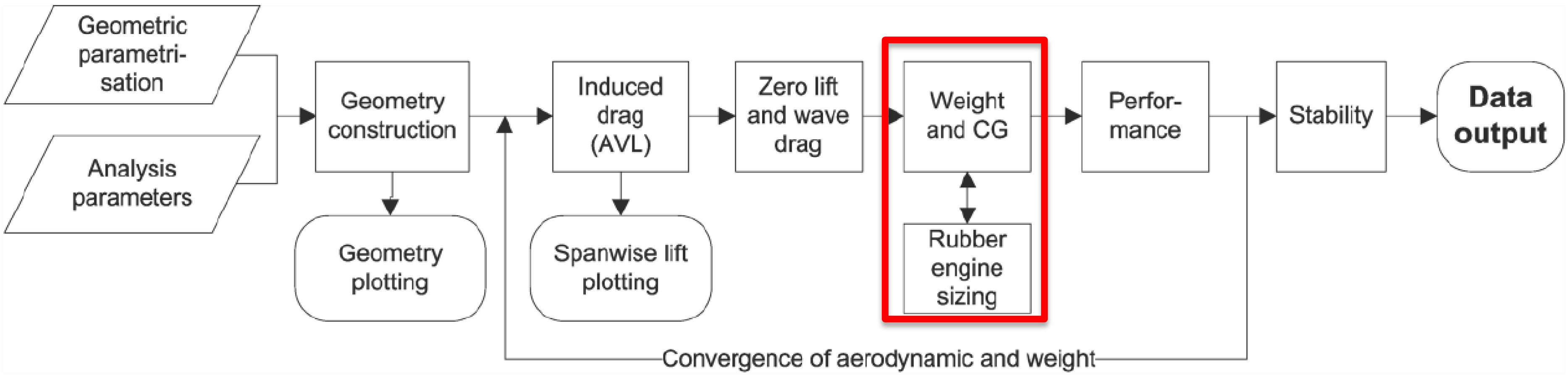
- Total zero lift drag calculated using strip theory
- Calculation of zero lift drag coefficient for each individual strip composing the fuselage and the wing
  - Calculation based on form factor and flat plate friction coefficient
  - Correction for local sweep and Mach number
- Integration over wing surface

$$C_{d_0} = C_f \cdot FF \qquad C_f = \frac{0.455}{(\log_{10} R)^{2.58}(1 + 0.144M^2)^{0.65}}$$

$$FF = \left(1 + \frac{0.6}{(x/c)_m}\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right)\left(1.34M^{0.18}(\cos\Lambda_m)^{0.28}\right)$$

CHAIRE IDEA CHAIR

BWB design – Global algorithm



CHAIRE IDEA CHAIR

BWB design – Components Weight

- Total weight calculation is done using components breakdown method
  - Many components are common to classic aircraft
  - Some formulas are specific to the blended wing body

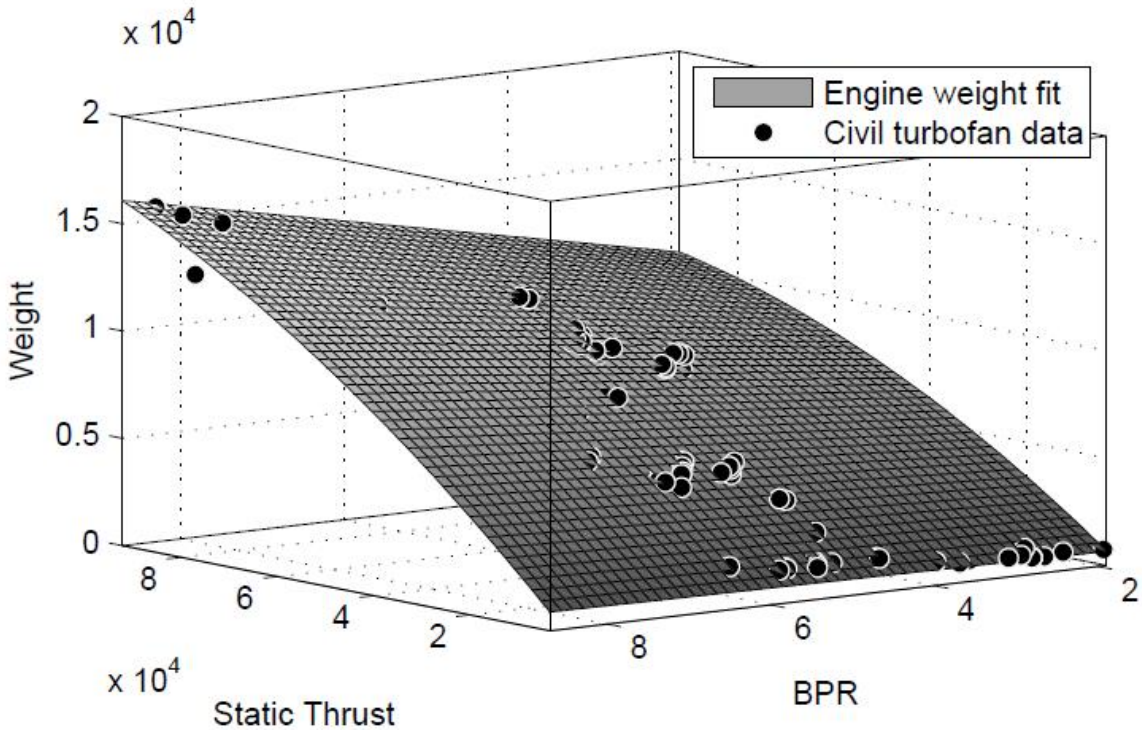
Composante	Note	Source
Fuselage	Régression basée sur une analyse par élément fini	Bradley (2004)
Fuselage arrière	Basé sur l'équation d'un stabilisateur horizontal ajusté pour supporter des moteurs	Bradley (2004)
Aile	Formule ajustée au ratio de portance supporté par l'aile, -15% si utilisation de composite	Viau (2008)
Moteur	Formule originale, développée à l'aide d'une régression	-
Nacelles	Commun aux avions classiques, -10% pour utilisation de composites	Raymer (2006)
Pylône	Commun aux avions classiques	Viau (2008)
Système de contrôle moteur	Commun aux avions classiques	Raymer (2006)
Systèmes carburants	Commun aux avions classiques	Viau (2008)
Démarreur moteur	Commun aux avions classiques	Raymer (2006)
Train d'atterrissage avant	Commun aux avions classiques	Torenbeek (1982)
Train d'atterrissage arrière	Commun aux avions classiques	Torenbeek (1982)
Surface de contrôle	Commun aux avions classiques	Viau (2008)
Systèmes hydrauliques	Commun aux avions classiques	Torenbeek (1982)
Système électrique	Commun aux avions classiques	Viau (2008)
Dégivreur	Commun aux avions classiques	Raymer (2006)
Accessoires	Commun aux avions classiques	Raymer (2006)
Unité de puissance auxiliaire (APU)	Commun aux avions classiques	Roskam (1990)
Peinture	Commun aux avions classiques	Roskam (1990)
Finition cabine	Commun aux avions classiques / Ajusté aux dimensions cabine du fuselage intégré	Divers

CHAIRE IDEA CHAIR

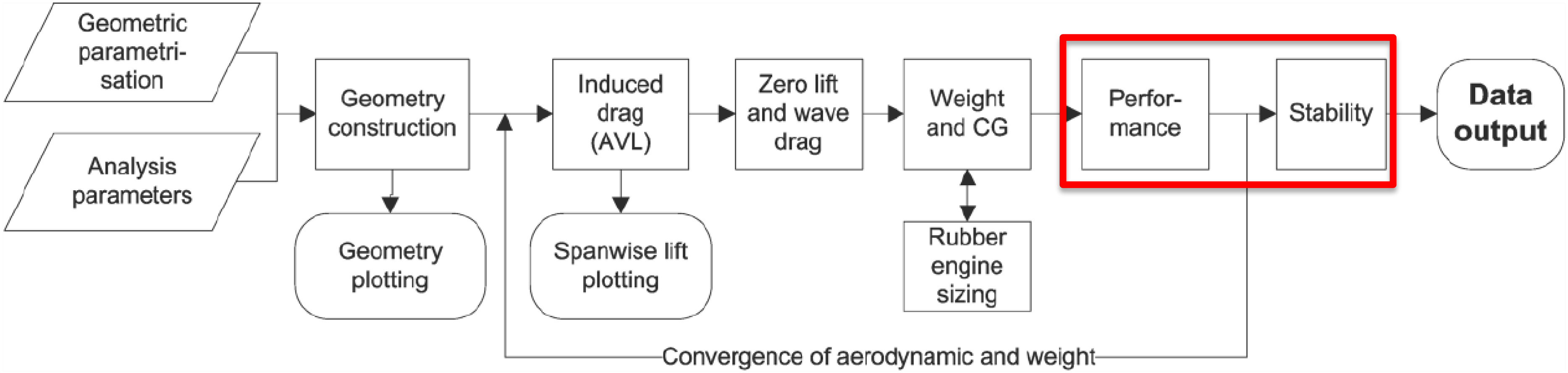
BWB design – Components Weight

- Engine weight estimated from an in-house correlation

$$EngineWeight = 37.31 + 0.01647 \cdot T - 7.161 \times 10^{-7} \cdot T^2 + 0.008675 \cdot T \cdot BPR$$



BWB design – Global algorithm



BWB design – Performance and Stability

- Performance computed from Breguet equation with corrections for taxi, climb and landing phases

- Static longitudinal stability calculations are made to estimate the stability margin

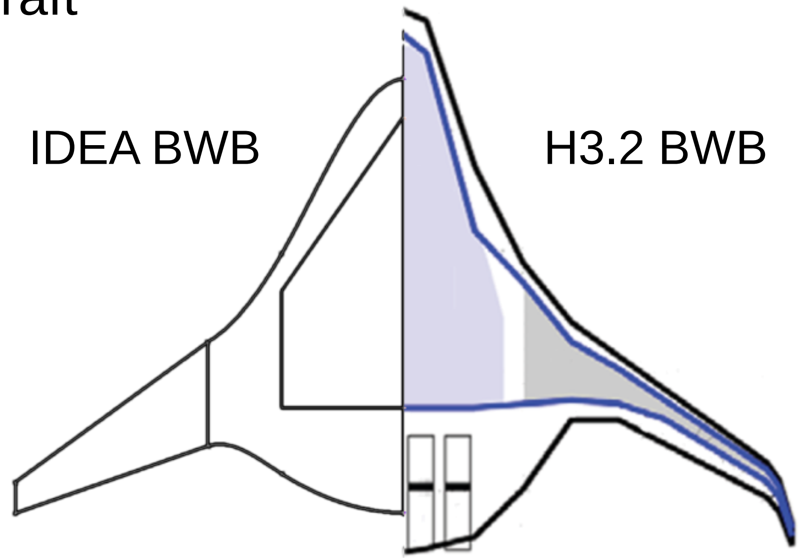
  - Neutral point is obtained from AVL
  - CG is obtained from weight calculation and components location
  - Finally, static margin can be approximated using:

$$SM = (X_{np} - X_{cg})/MAC$$

CHAIRE IDEA CHAIR

BWB design – Validation

- Comparison to NASA H3.2 BWB Aircraft
    - Same mission
    - Same payload
    - Same technology level

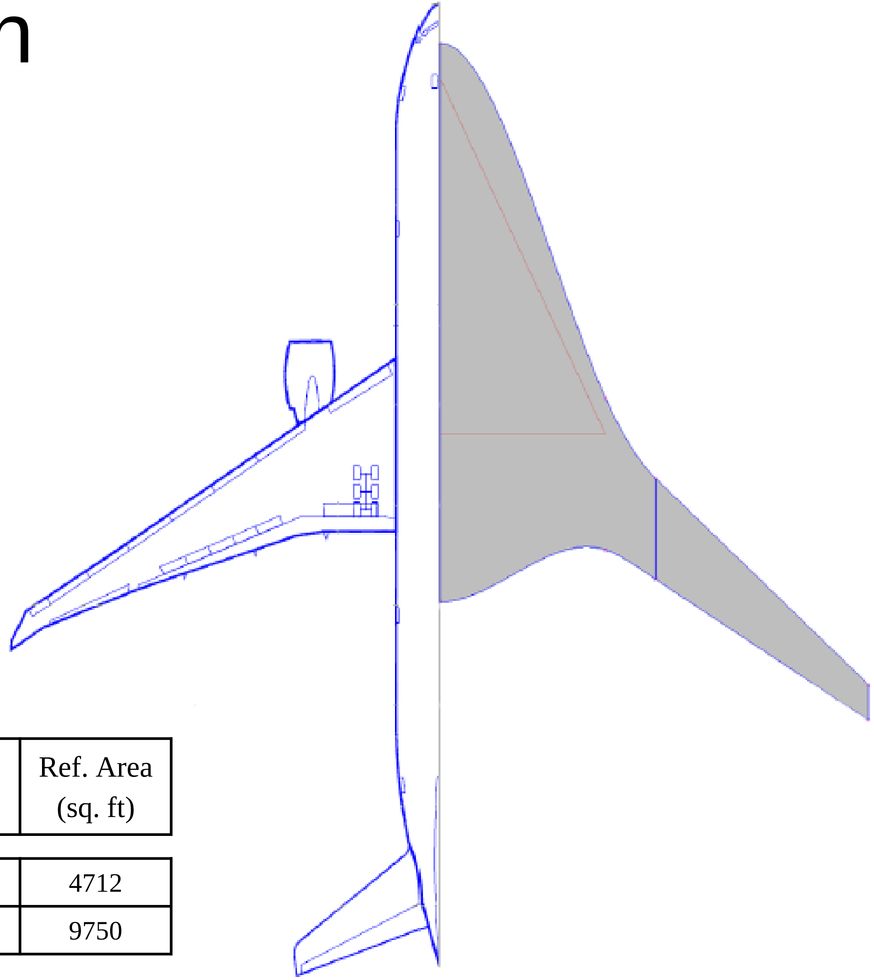


	MTOW (lbs)	OEW (lbs)	Fuel (lbs)	Ref. Area (sq. ft)	Length (ft)	Span (ft)
H3.2 BWB *	470566	209976	126159	10149	147.96	213
Equivalent design	470104	208920	126749	9750	117	210

* Greitzer, Bonnefoy & al., e. (2010). *N+3 Aircraft Concept Designs and Trade Studies* , NASA 2010-216794. Cleaveland, Ohio: Glenn Research Center.

BWB design – Validation

- Classic aircraft comparison
  - Boeing 777-300ER
  - 365 passengers
  - Range 7600 nm



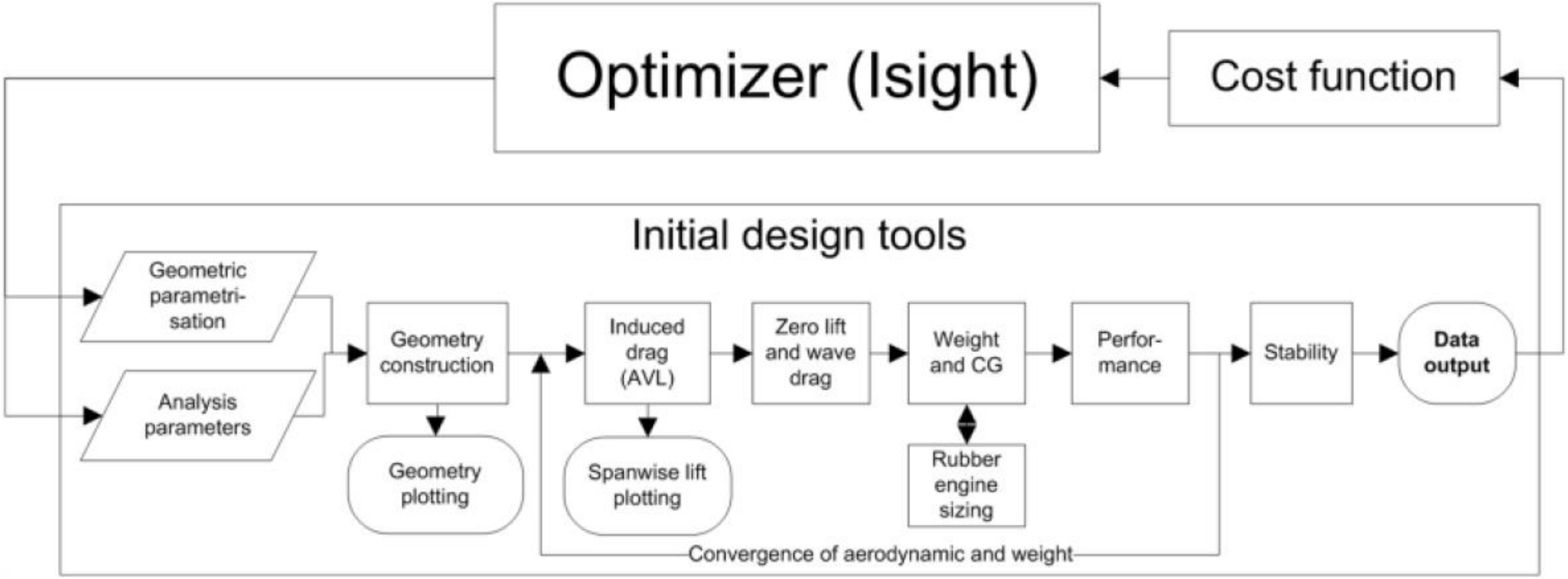
	MTOW (lbs)	OEW (lbs)	Fuel burn (lbs)	Length (ft)	Span (ft)	Ref. Area (sq. ft)
777-300ER	775000	370000	312075	242'4"	212'7"	4712
BWB design	674585	329230	252430	117'	210	9750
Variation:	**-14.9%**	**-12.4%**	**-23.6%**			
Liebeck *	**-15%**	**-12%**	**-28%**			

* Liebeck, R., Page, M., & Rawdon, B. (1998). *Blended-wing-body subsonic commercial transport*. Paper presented at the 36th Aerospace Sciences Meeting & Exhibit, Reno, NV.

CHAIRE IDEA CHAIR

Low Fidelity MDO

- **Strong interaction between geometry, weight and stability observed using manual iteration**
- **Large exploration of design space can be better performed using optimizers**

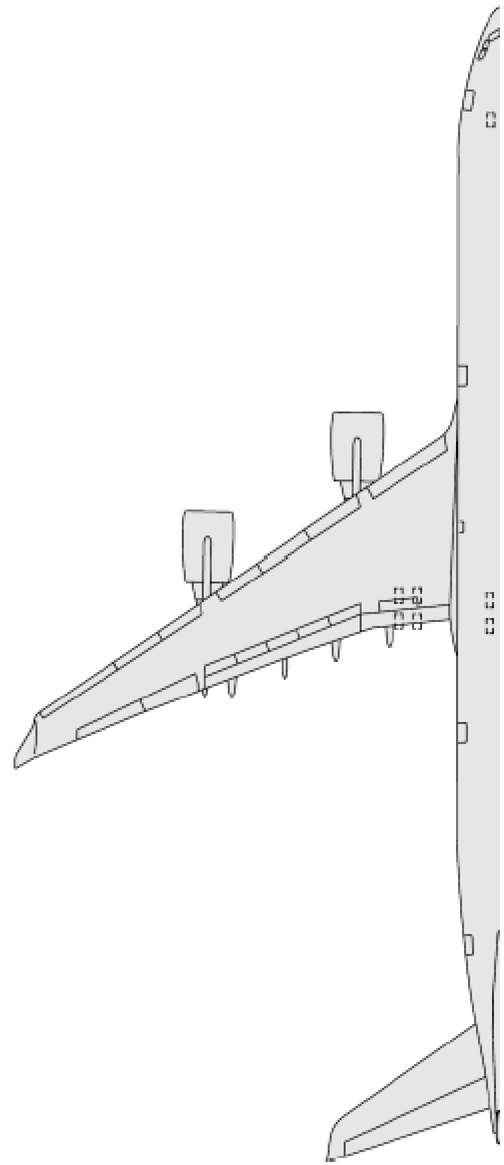


CHAIRE IDEA CHAIR

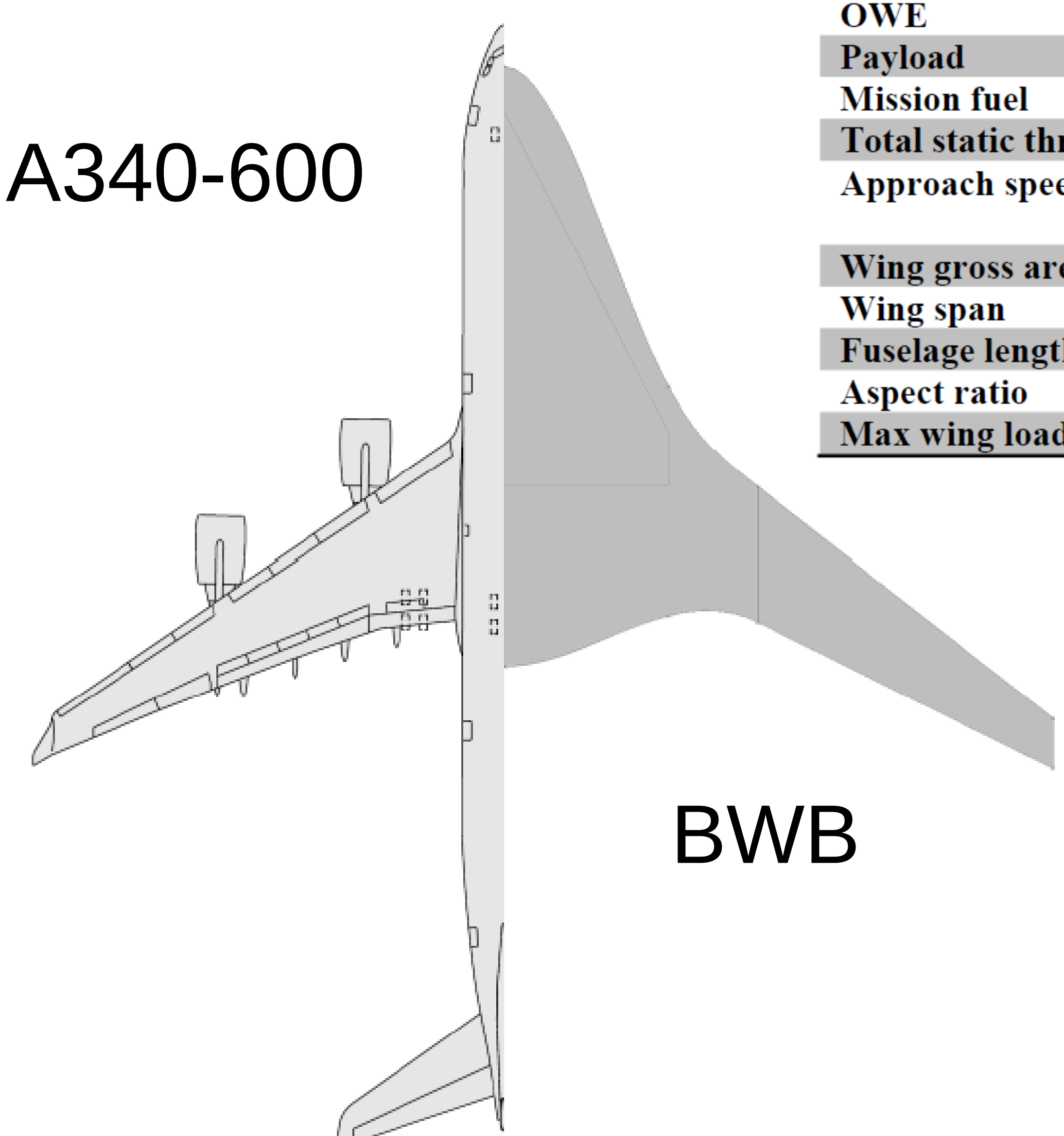
Low Fidelity MDO – A340-600

- **Cost function: Minimize MTOW**

Constraints and parameters	Value
Range	= 7350 nm
Available fuel volume	Larger than required fuel
Balance field length	<= 10365 ft
Cruise altitude	= 39000 ft
Cruise speed, Mach	= 0.82
Static longitudinal stability margin	> 0.05
Passenger capacity	>= 380
Cruise TSFC (RR Trent 556)	= 0.54
Bypass ratio	= 7.61
Span	<= 240 ft
Number of engines	2
Material	All aluminium



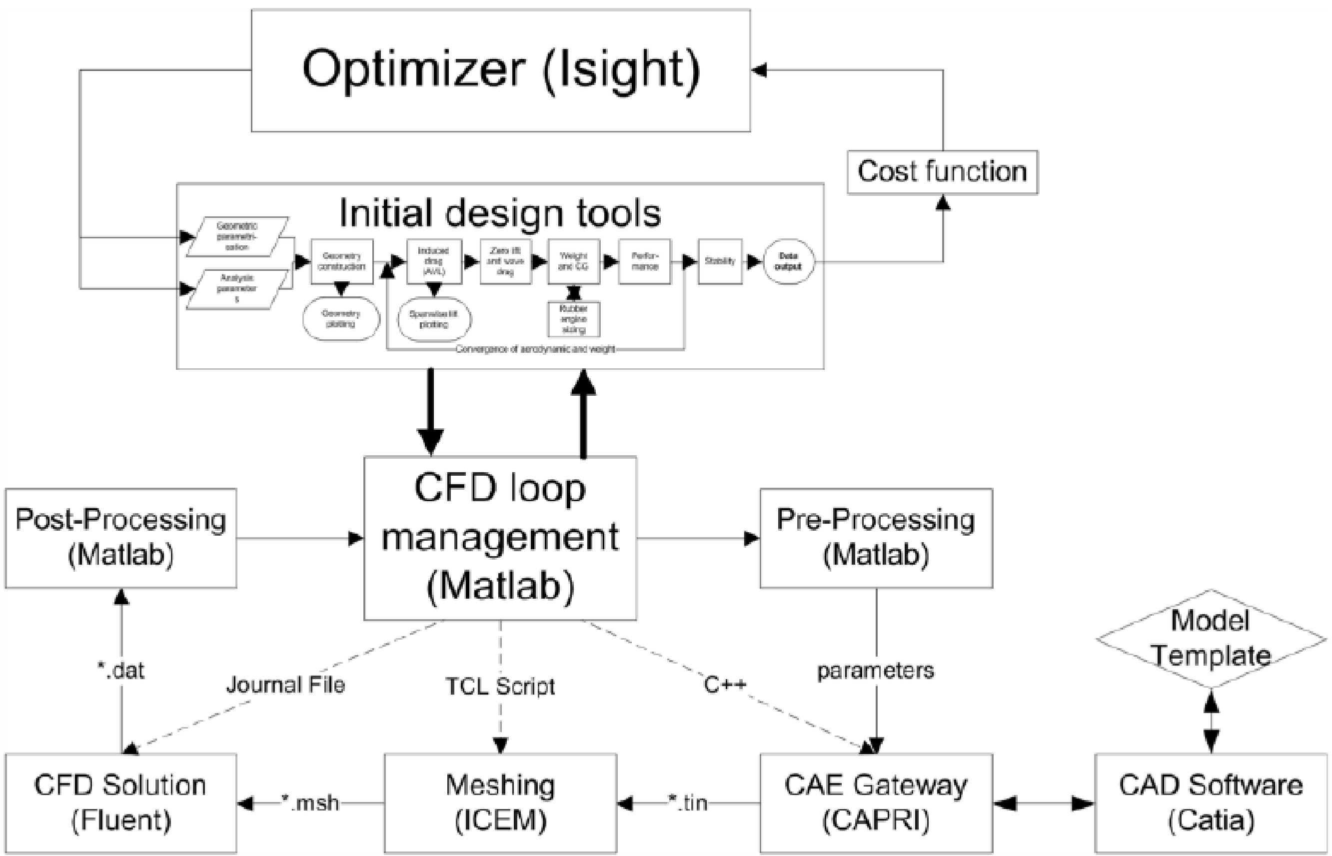
CHAIRE IDEA CHAIR



Specification	Optimized BWB	Airbus A340-600
MTOW	639016 lb	811300 lb
OWE	319200 lb	391760 lb
Payload	85500 lb	85500 lb
Mission fuel	234319 lb	334040 lb
Total static thrust	141614 lb	224000 lb
Approach speed	144 kts (at MTOW)	144 kts (at MLW)
Wing gross area	10965.2 sq ft	4703.8 sq ft
Wing span	240 ft	208 ft 2 in
Fuselage length	131.1 ft	245 ft 11 in
Aspect ratio	5.25	9.3
Max wing loading	58.3 lb/sq ft	171.07 lb/sq ft

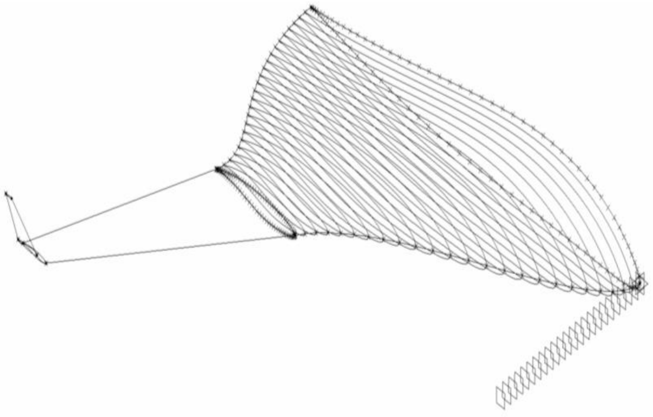
‖ High fidelity optimization

Limitations of low fidelity models : 3D transonic aerodynamics



High fidelity – Capri Gateway

- DriveMM is used to create the link between Matlab and Catia
  - Read, analyse, modify, update and save a CAD model
- CAPRI2tetin is used to convert a CAD model in a native ICEM geometry file (*.tin)
  - CAPRI2tetin allows to keep a unique set of face names and allows automation of the mesh
  - The geometry is exported using B-splines.

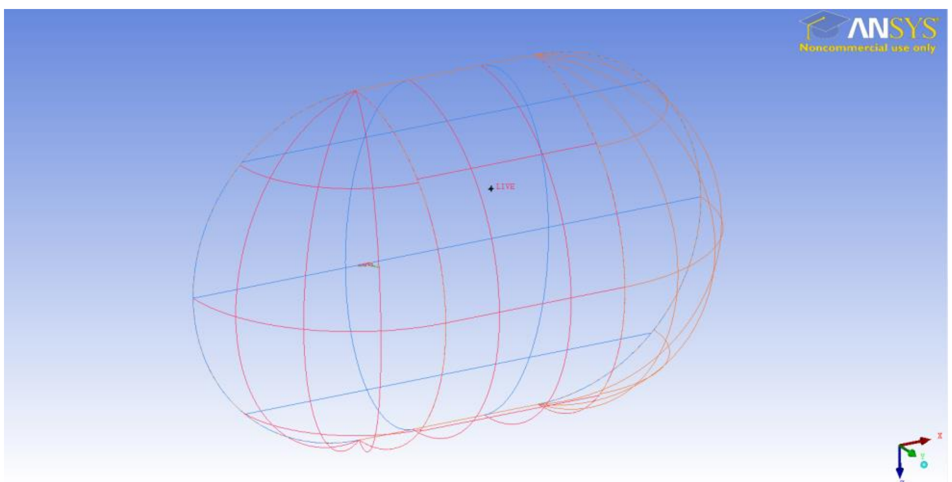


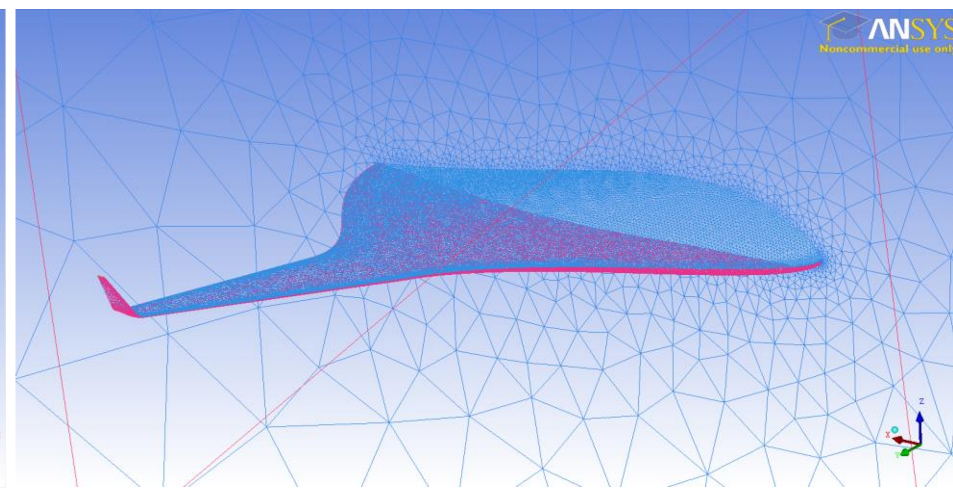
High fidelity – ICEM meshing

- ICEM is used to mesh the 3D model for CFD analysis.

- The meshing is automated and run in batch mode
  - Scripting using TCL language, the domain is constructed in ICEM

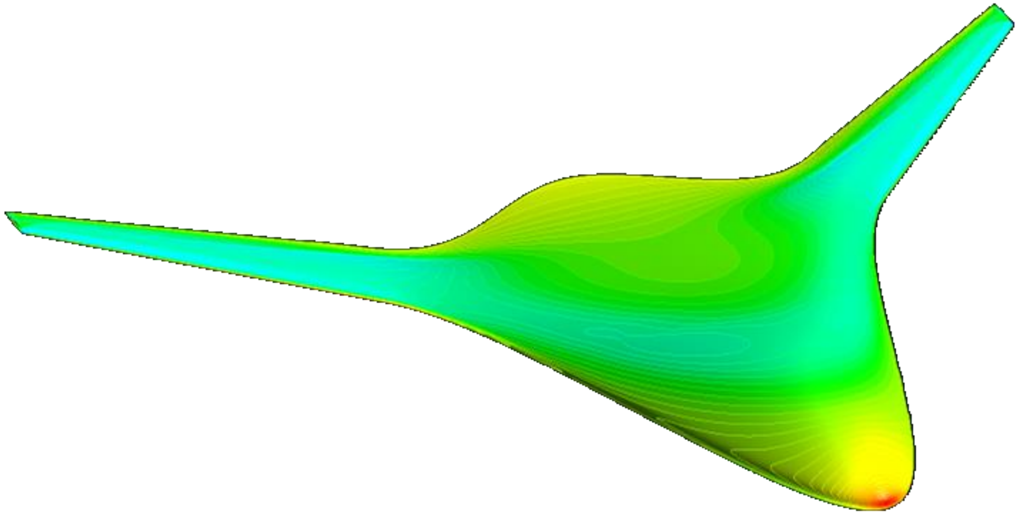
- Mesh specification
  - Tetrahedral mesh for speed, flexibility and simplicity.
  - Approximately 1M cells
  - Generation in less than 1 minute





High fidelity – FLUENT fluid solver

- CFD calculations is done with Fluent
- Compressible, inviscid (Euler) analysis
  - Reduced computation cost: lower mesh size and reduced number of equation to solve
- Convergence of residual to 10^{-6}, calculation time under 5 minutes



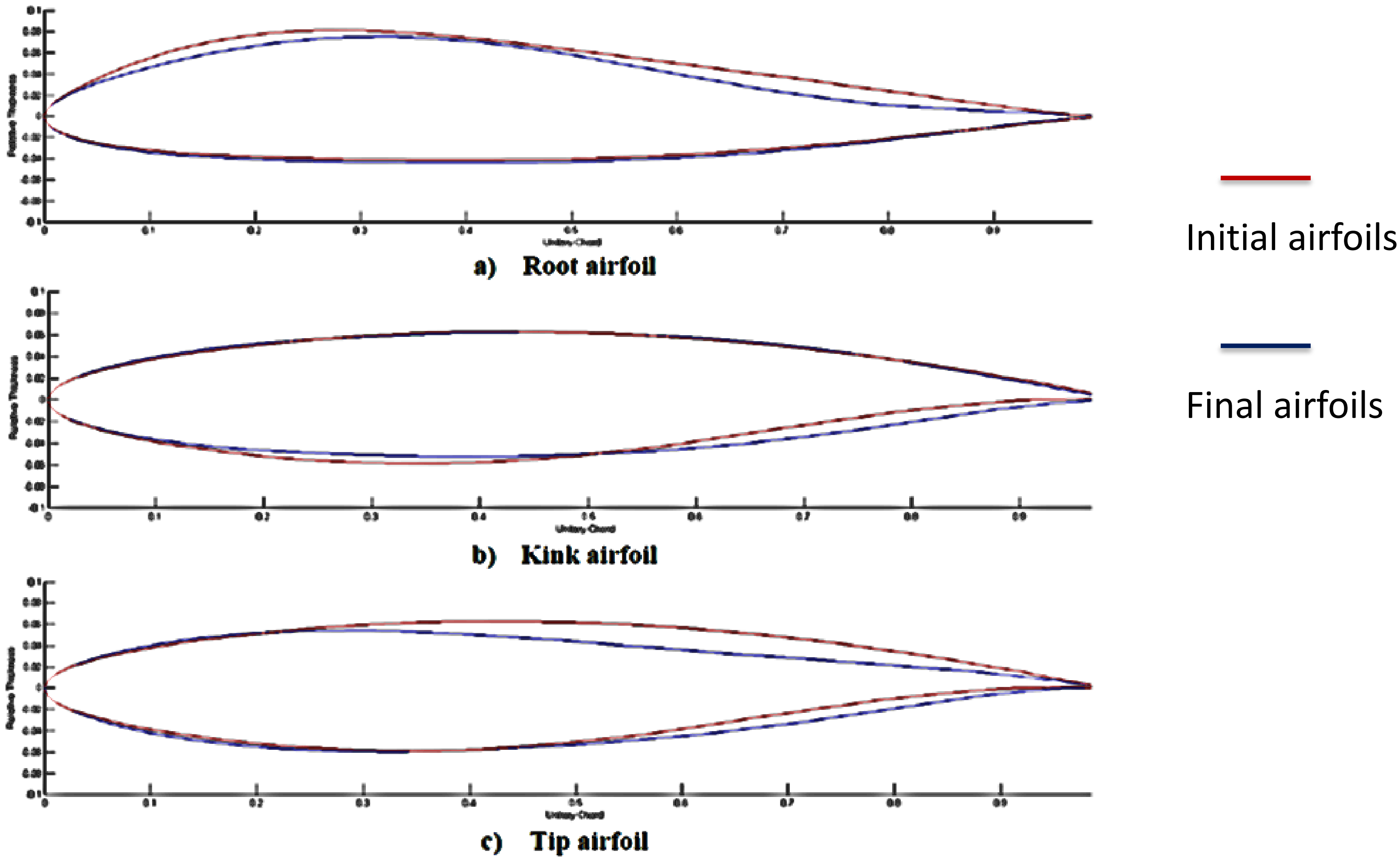
High fidelity – Optimization

- A340-600 aircraft *vs* BWB
- Fixed planform
- 33 PARSEC airfoil geometric variables
- First optimization to reduce pitching moment
- Second optimization to reduce L/D

Specification	Initial model	First solution with satisfied constraints	Final solution
L/D (CFD)	17.06	16.01	16.96
Trim offset	18.5%	9.6%	9.9%
Fuel weight (lbs)	234320	231871	235242
Static longitudinal stability	5.01%	4.98%	4.95%

CHAIRE IDEA CHAIR

High fidelity – Optimized airfoils



Conclusion

- Initial BWB design method
  - Allow to reproduce NASA work
  - Allow to redesign various classical aircraft
  - BWB shows important gain in fuel burn
- Low fidelity optimization
  - Facilitate the search for stable aircraft
- High fidelity optimization
  - Feasibility of Matlab-CATIA-ICEM-FLUENT integration
  - Limitations of Euler solutions (no viscous drag)
  - Limitations of Parsec parameterisation

Future Work

- Initial BWB design method
  - Compressibility drag empirical formula (Korn equation)
  - Climb rate at cruise altitude + engine model at altitude
- Low fidelity optimization
  - Design exploration: add more constraints, objective functions etc.
- High fidelity optimization
  - Automation of block-structured meshes
  - Solve Navier-Stokes equations
  - Use drag decomposition method for better comparison with AVL
  - Possibly change Parsec parameterization