Recent Advances in Variable Fidelity MDO Framework for Collaborative and Integrated Aircraft Configuration Development - CEASIOM

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Overview and Summary

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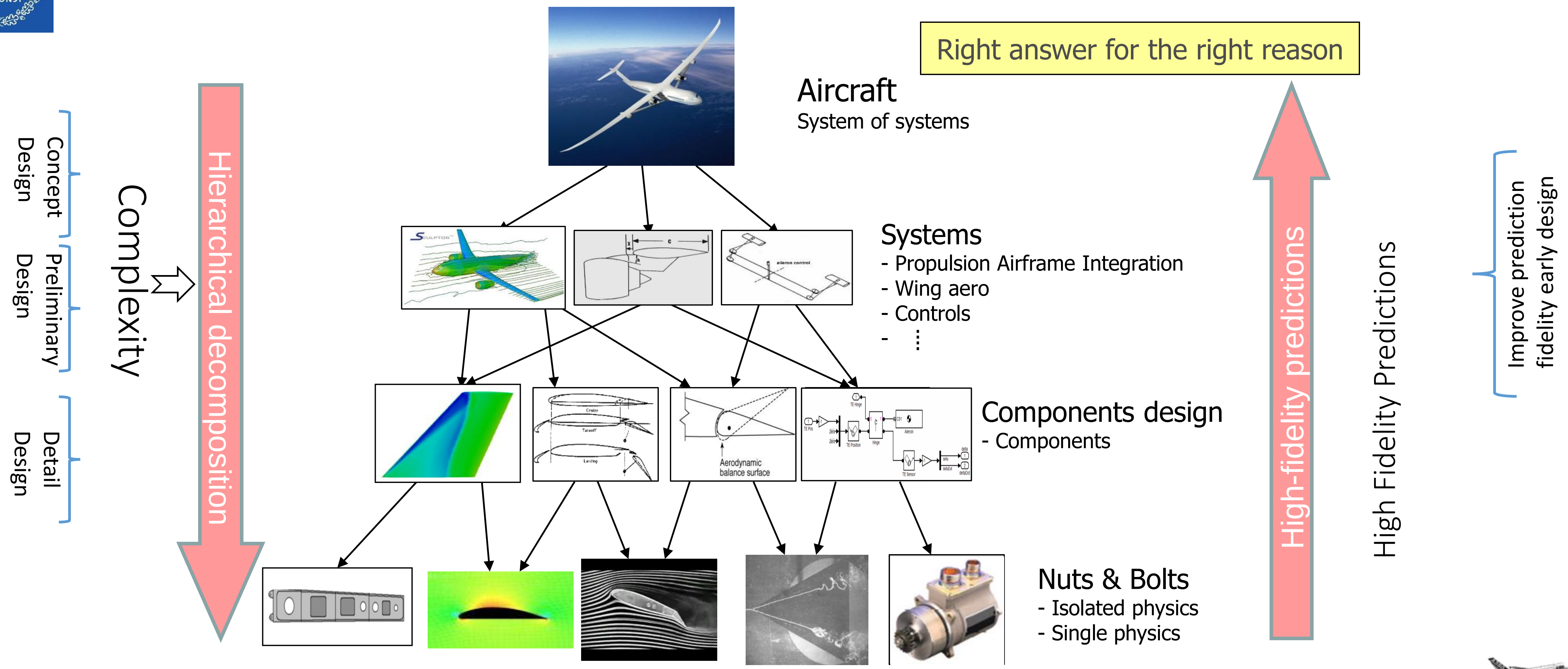
- Introduction to aircraft conceptual-preliminary design
- Software for aircraft conceptual-preliminary design
- Wing design methodology
- Results and discussion of selected design studies
- Conclusions

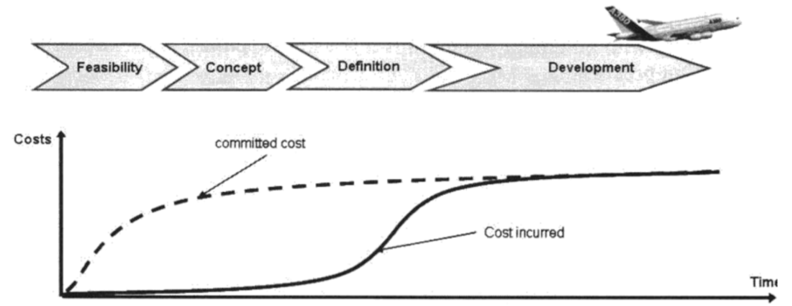
Re-engineering the aircraft design process

Goal → From functional-oriented approach to an integration of all disciplines

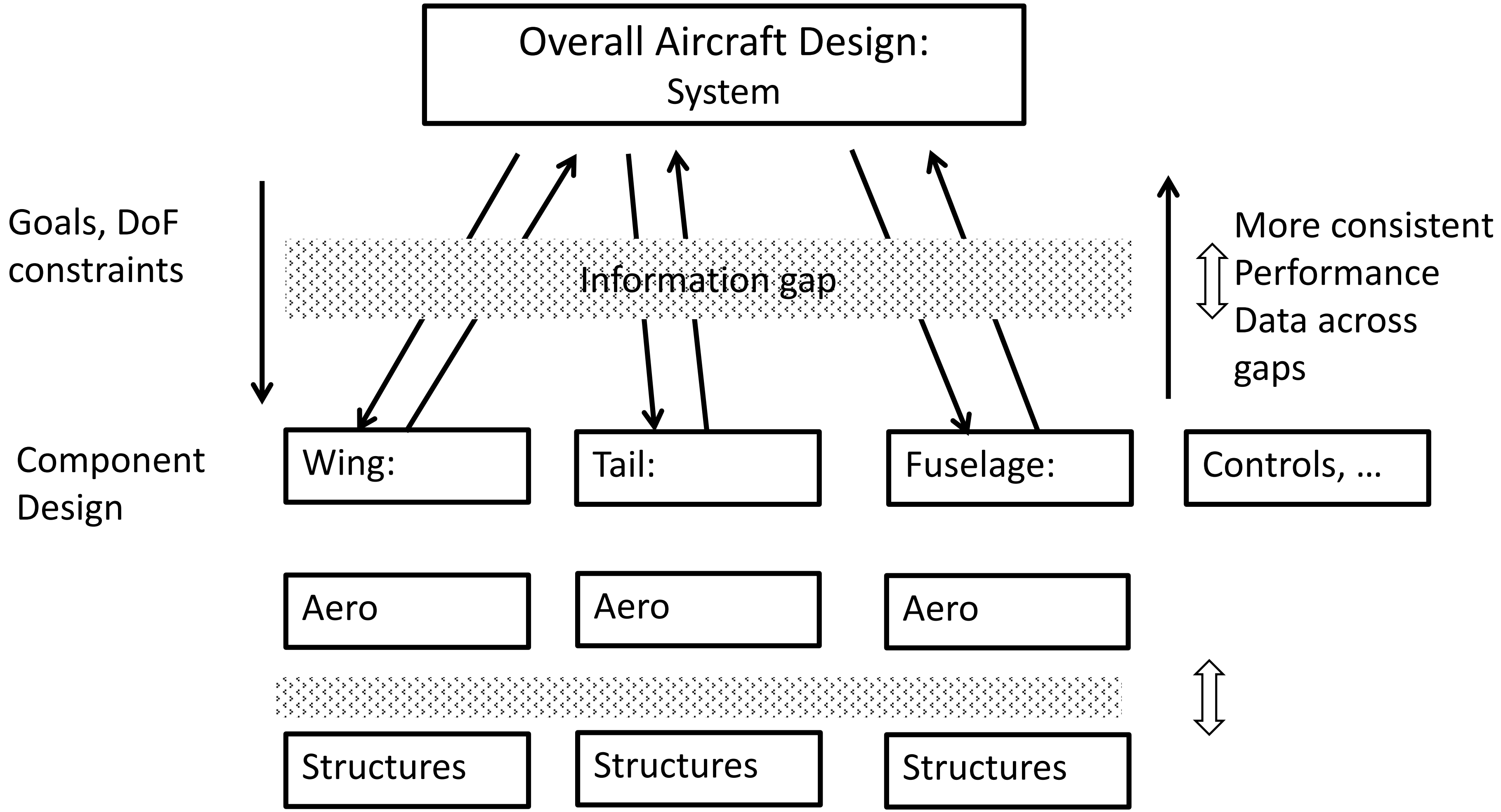


Top down: Requirements-based priorities for design concept

Bottom up: Hi-fi predictions of concept performance



Ways to Improve Prediction Fidelity in early Design



Revised Layout Example: TCR T-tail → TCR Canard

CEASIOM

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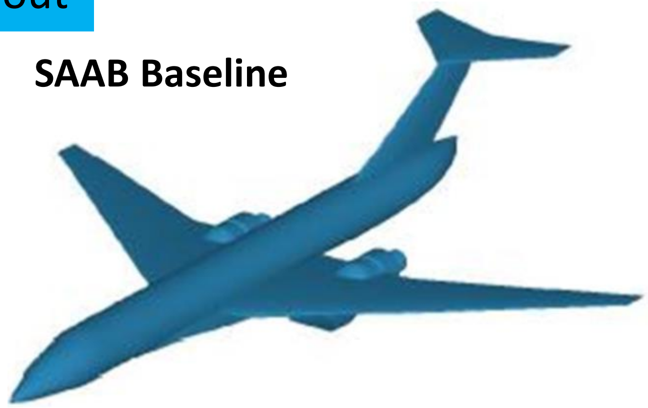
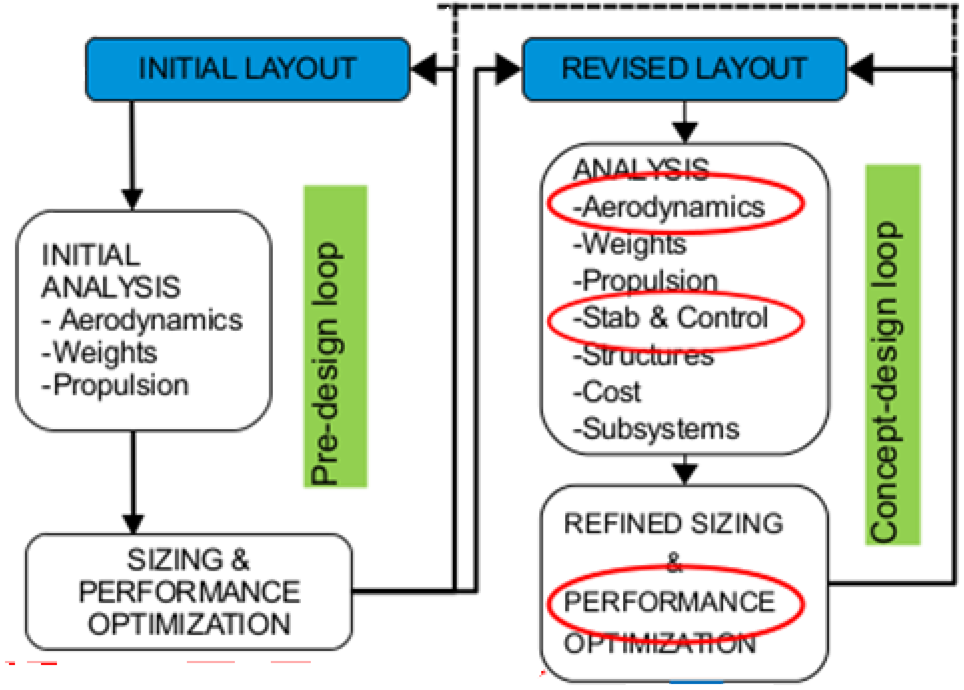
Initial Layout

- **Payload**
  - MTOW ~~108 t,
  - No. Pax ~ 200
- **Range**
  - ~10.000 km (5.500 nm)
- **Design Cruise speed**
  - Mc = 0.97

SAAB Baseline





- **Original TCR T-tail: poor trim ability**
  - → large α, δ
- **3 revised layouts investigated**
  - Wing further fore (design parameter)
  - Three lifting surfaces
  - All-moving canard (vary location & size)

Revised Layouts

Objectives, Scope & Structure

Objective: Improve CEASIOM software to better **alleviate information gaps**:

- Recent advances in CEASIOM
  - Extend CEASIOM by adopting CPACS data base and format → higher ***order*** geometry
  - Define/import/create "Initial Layout" for CEASIOM → higher ***fidelity*** analysis
  - Implement Data Fusion to build Database from various models
  - Create ***Aerodynamic shape optimization*** toolbox
- Scope
  - Demonstrate airframe geometry modeling and its import function on different aircraft concepts
  - But structural modeling & complete support for RANS modeling out of scope
  - Subtask within MDO, via task decomposition, focusses on aerodynamic shape optimization
- Structure of this talk
  - 2 explains early CEASIOM & "New" CEASIOM
  - 3 describes shape optimization techniques & tools
  - 4 presents results obtained with new CEASIOM contributions
  - 5 concludes with lessons learnt
  - 6 Future work

2. Software for aircraft conceptual-preliminary design

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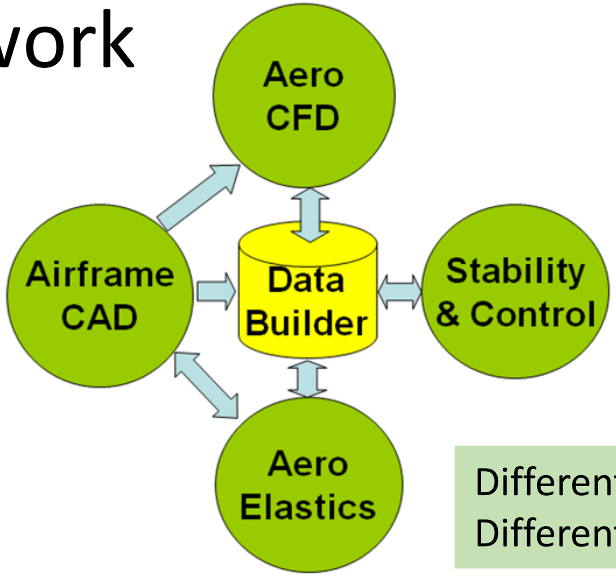
- Data-centric Scheme for MDO framework: **CPACS**
- *Early* CEASIOM
- Recent advances: **New** CEASIOM
  - Adoption of CPACS – support for collaborative and integration
  - Baseline configurations from several sources
  - Higher fidelity geometry and meshable models from CPACS
  - Meshable models – the key to physical-based analysis
  - Database building by data fusion
- **Optimization** process

Need for Open Data-Centric Framework

Framework Challenges are: (Salas)

- Extensibility & interfaces
- Support collaborative design
- Data compliance
- Module exchangeability
- Based on *standards*



Different design teams
Different fidelity analysis

Collaborative Design Enabled by *Open Data-Centric* Approach

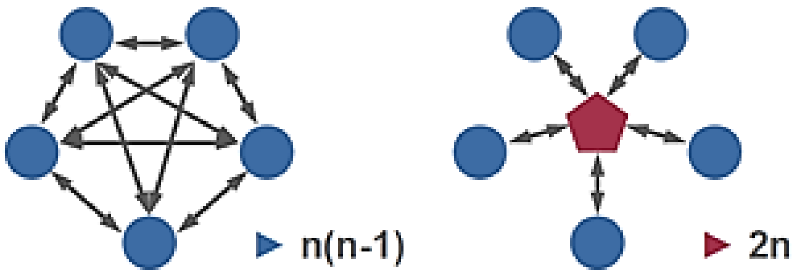
Common **P**arametric **A**ircraft **C**onfiguration **S**chema

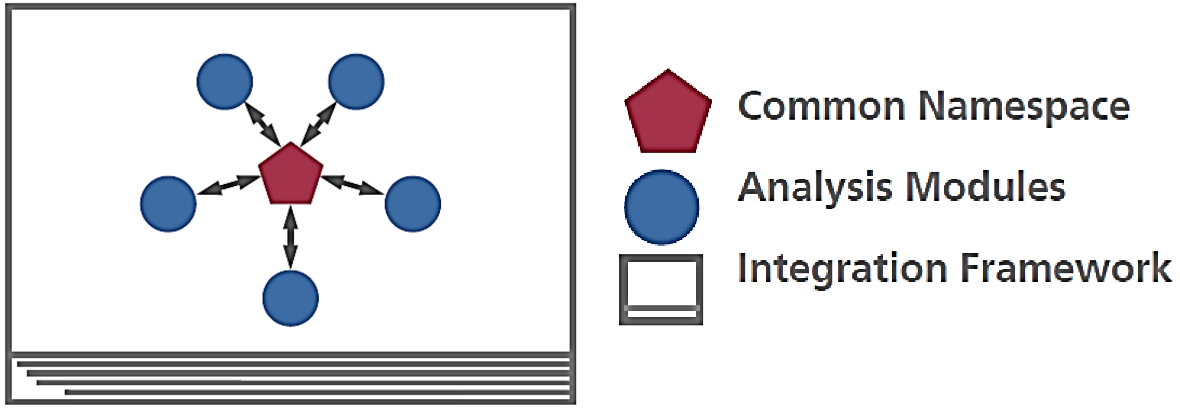
Parametric Model XML Data Format

Data-centric framework for MDO

- Across DLR Laboratories
- Open Source

Data-centric advantage



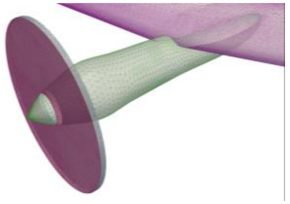


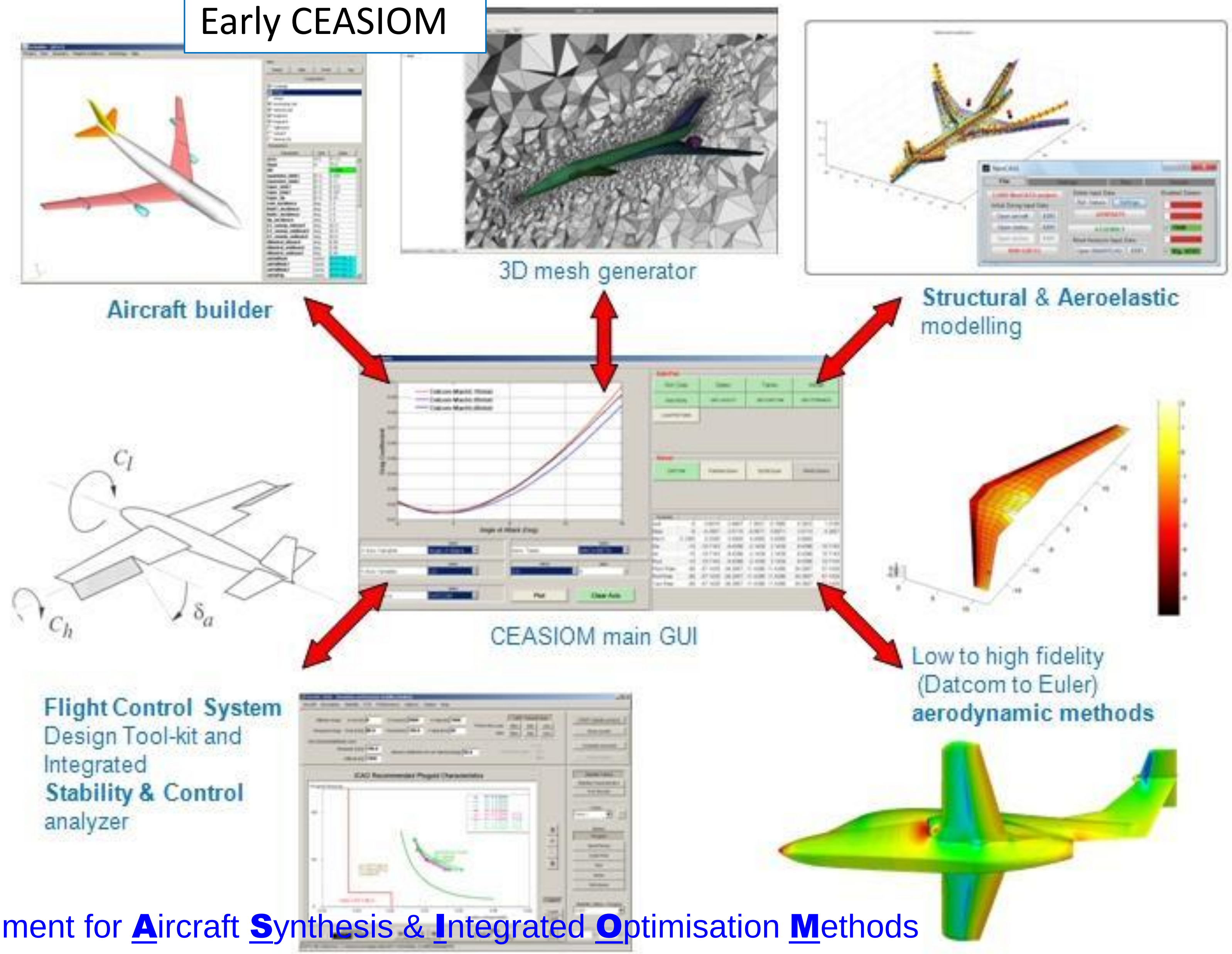
Adoption of CPACS → Support for Collaboration & Integration

Limitations in *Old* CEASIOM Design Framework

Contributions to *NEW* CEASIOM

1. Baseline configuration entered manually
2. Dataset (xml) defined ad hoc:
   1. Impairs collaboration & integration
   2. Geometry limited to
      1. 2-kink wing
      2. Cone-tube fuselage
3. No support for building aero databases
4. Difficult to model control surfaces & effects
5. No propeller model
   1. cannot simulate nacelle/wing/slipstream
6. **No Optimization !**





Computerised **E**nvironment for **A**ircraft **S**ynthesis & **I**ntegrated **O**ptimisation **M**ethods

Recent advances: New CEASIOM

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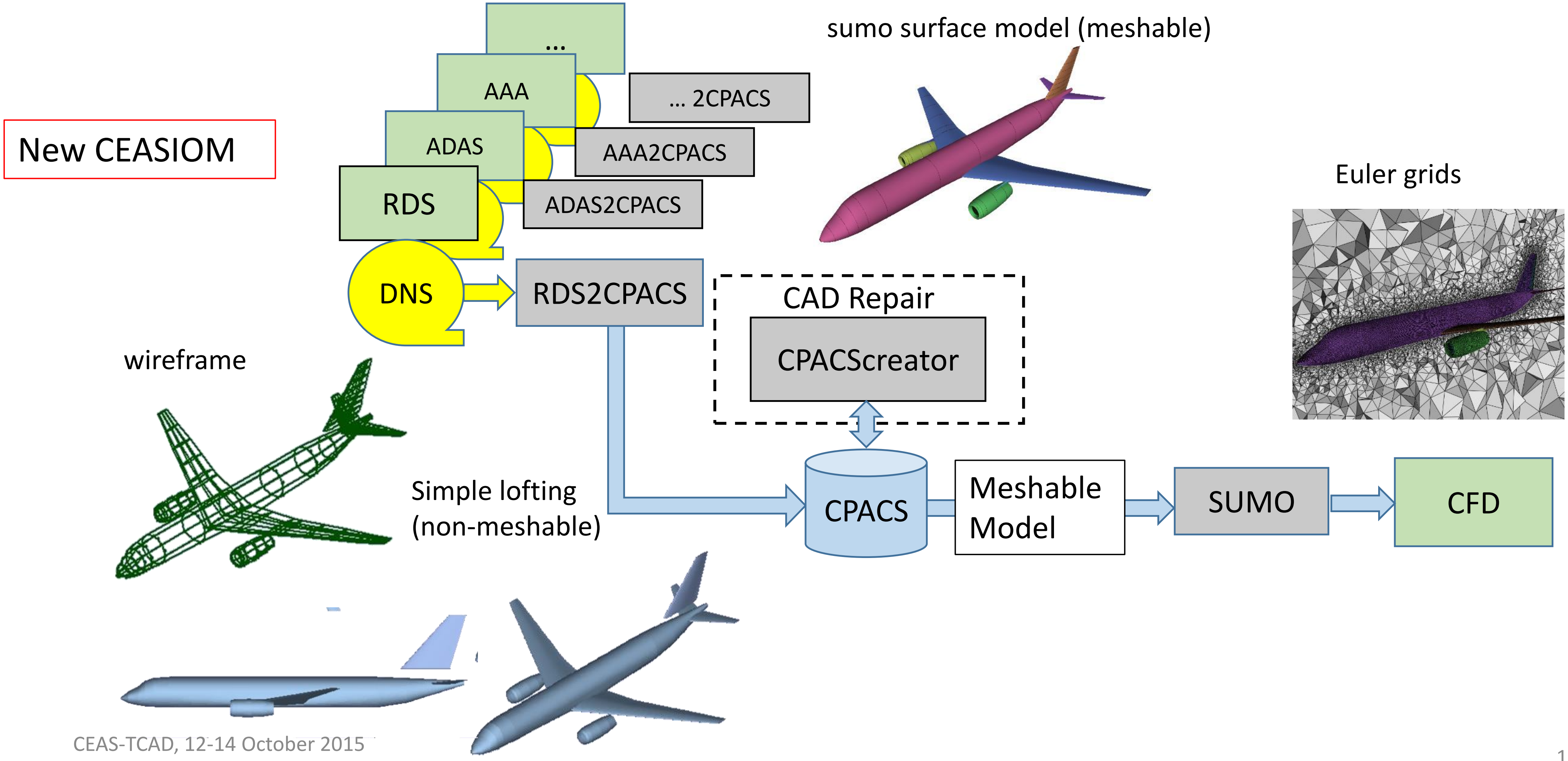
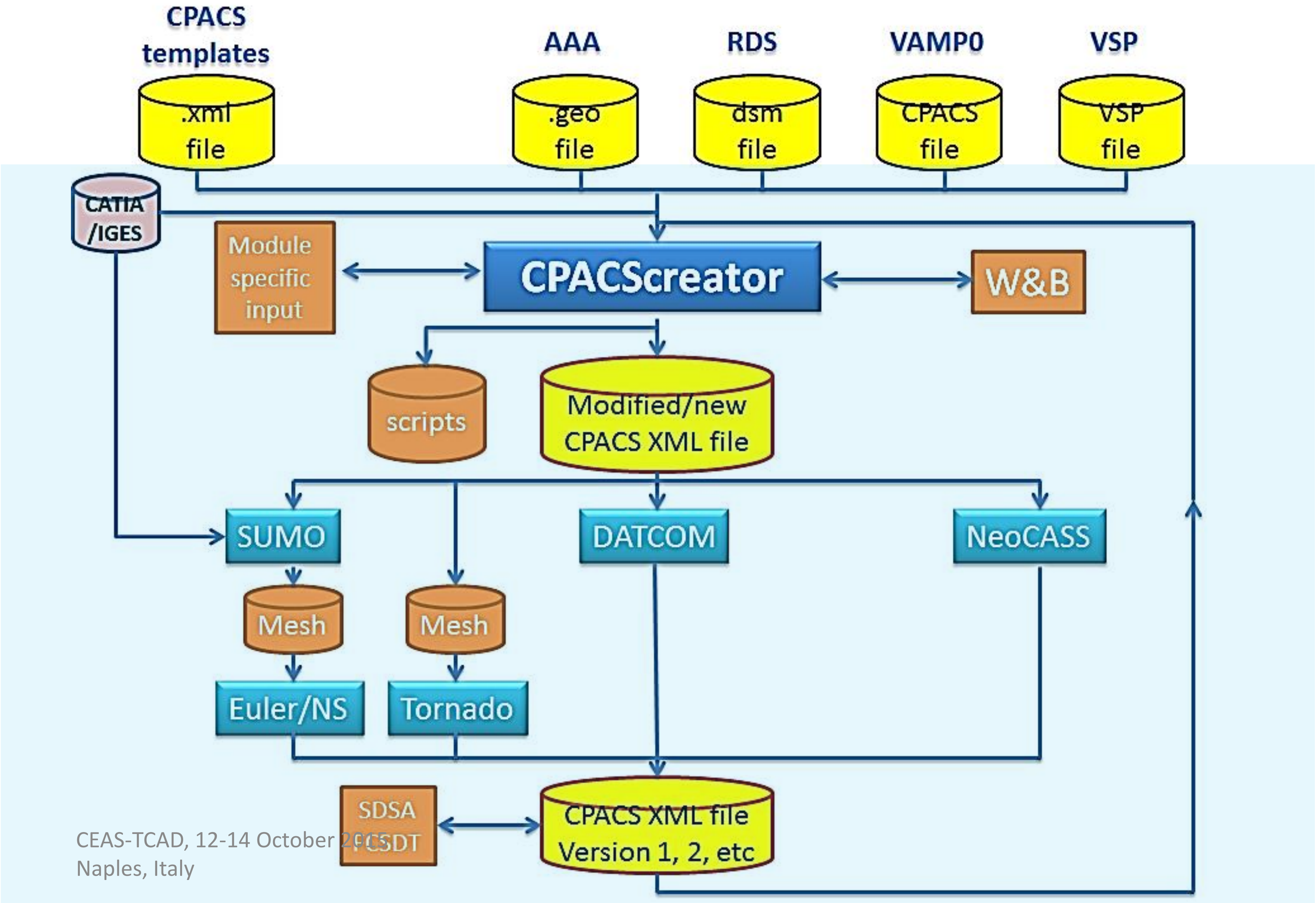
Meshable Models - the Key to Physics-based Analysis



CEASIOM / CPACS



New CEASIOM by adopting CPACS

Higher fidelity geometry and meshable models from CPACS

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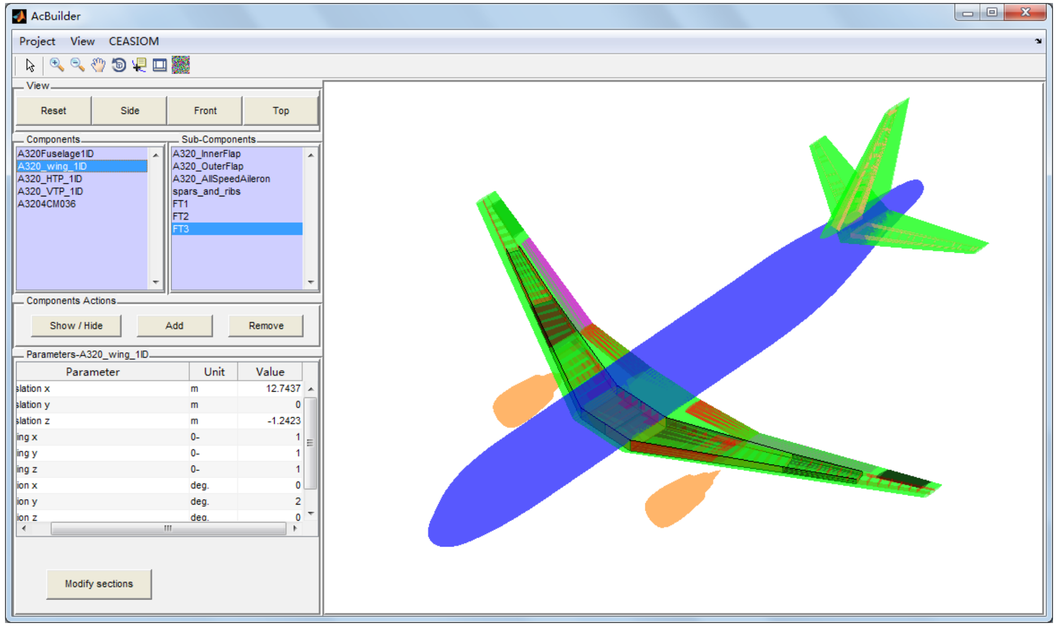
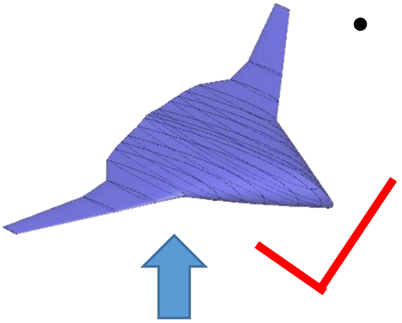
CPACScreator: visual renderer/editor of CPACS XML file

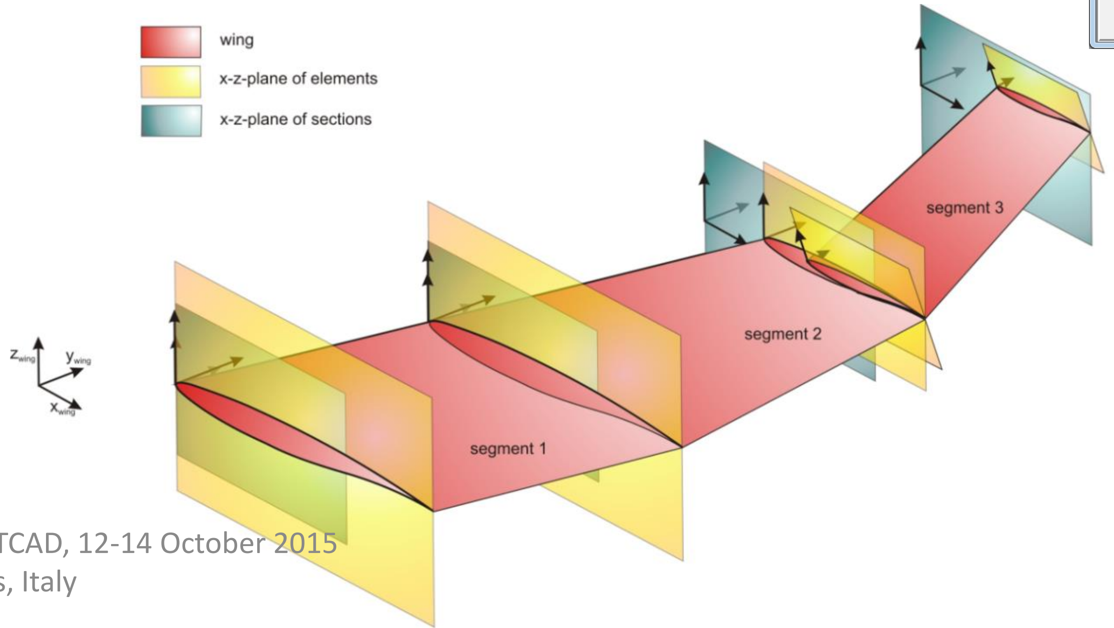


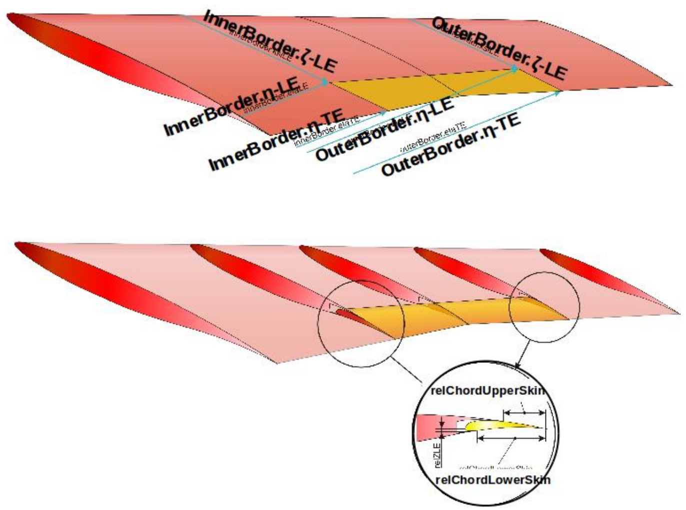
CPACS Wing ⇨ Airfoil stack

- "N-airfoil" wing: N-2 kinks
- TE control surfaces
- Each section
  - Airfoil (**point cloud**)
    - Camber, thickness
  - Incidence
  - Dihedral



possible!



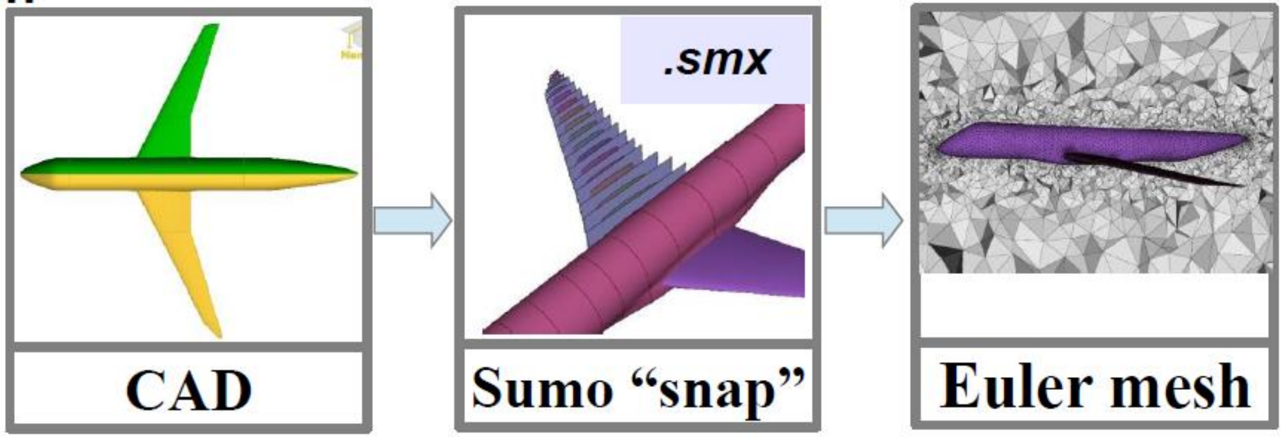


Rapid mesh tool *sumo*: CAD-> grids

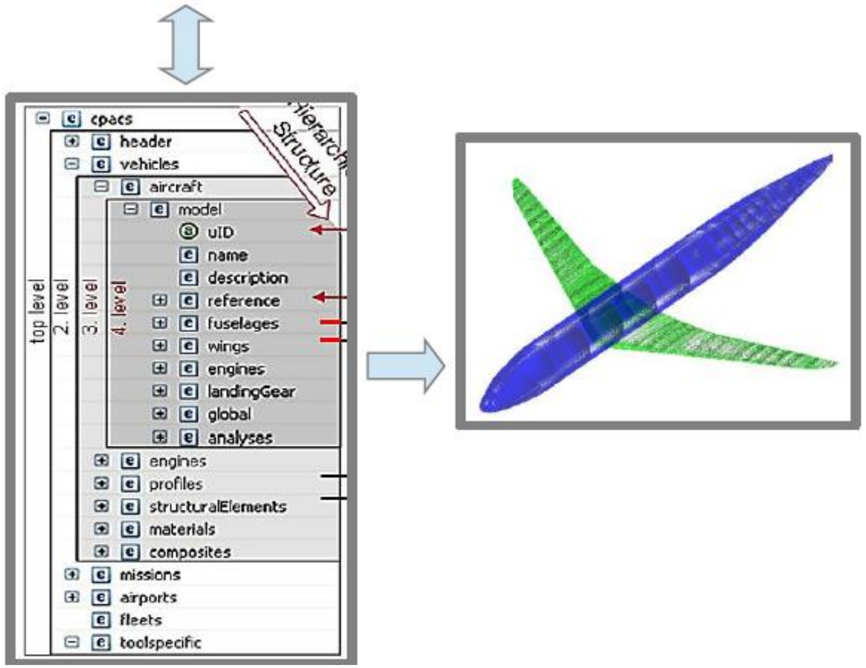
- Use **SUMO "snap" function**
- → IGES to CPACS

  ~ "shrink wrap"
- Open **`.smx`** SUMO geometry
- Load CAD geometry as overlay visualized in sumo

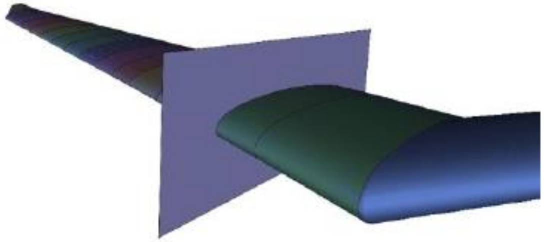
  `.igs, .stl, .catia` (?)
- Fit sections of lifting surfaces – needs user intervention



CPACS



- Save as **`.smx`**
- Export as CPACS



Disciplinary Data Fusion Tool

Utilize the DACE Toolbox

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$$\hat{f}(x^*) = \underbrace{\sum_{h=1}^{n} \beta_{h,k} f(x_h)}_{\text{Mean value}} + \psi_p^T \Psi^{-1} \underbrace{\left(f(x) - \sum_{h=1}^{n} \beta_{h,k} f(x_h) \right)}_{\text{weightings}}$$

Mean value *Linear regression* **weightings**

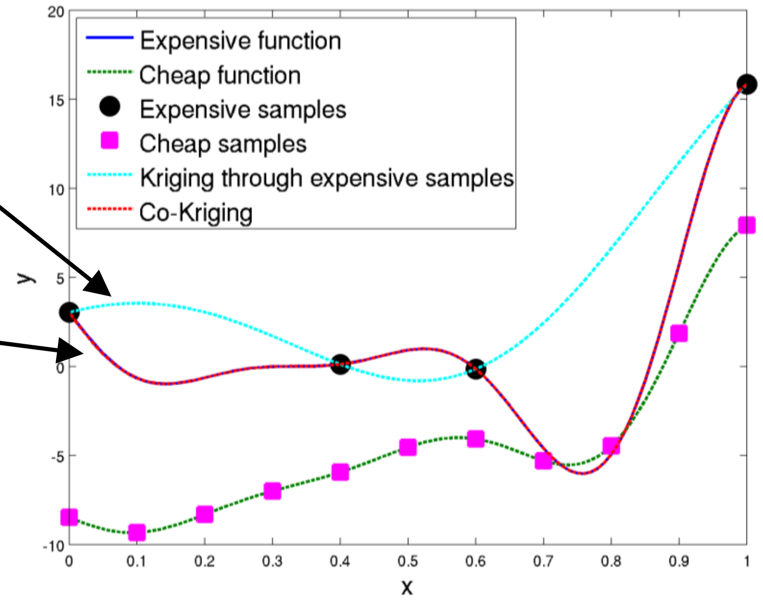
$$\psi_p(x^*, x^{(k)}) = \exp\left(-\sum_k \theta_k |x^{*(k)} - x^{(k)}|^{p_k}\right)$$

$$\Psi_{i,j} = \psi_p(x_i, x_j)$$

Kriging

Co-Kriging

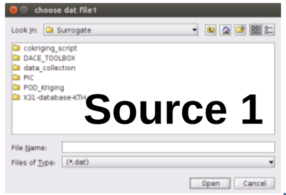
Variable Fidelity

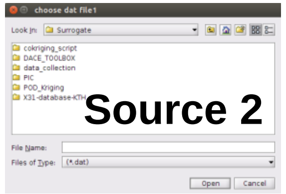


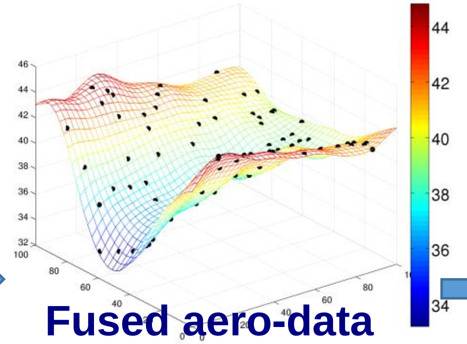
- Sampling
- Fusion
- Surrogate modeling
- Error tracking

Aero-data from individual tools

1. text files
2. XML files
[data.Aero.Table, ...]



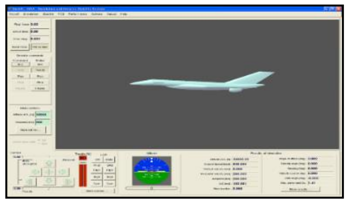


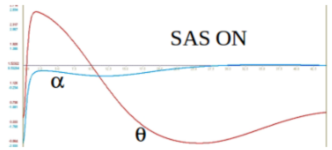


Fused aero-data

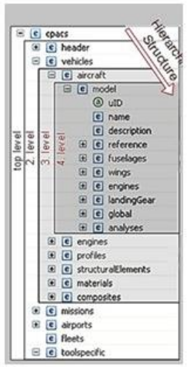
1. text files
2. XML files
[data.Aero.Table, ...]

SDSA table





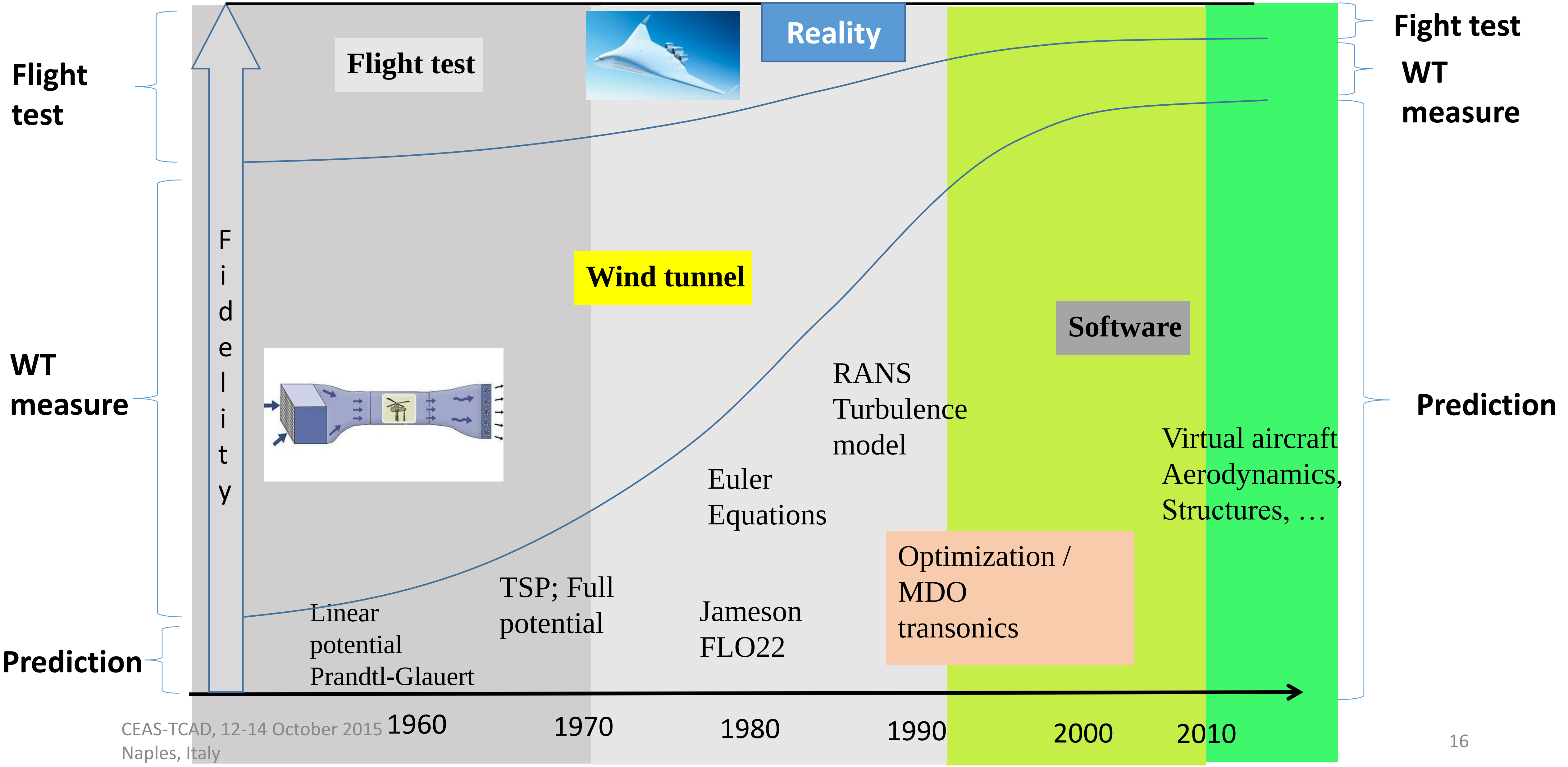
CPACS



3. Wing design methodology

- Aerodynamic wing design: historical trends
- Wing design procedure in industry
- Wing design approach: a procedure
- “mix” of 3 optimizer combinations
  - CEASIOM-OPT Matlab scripts
  - SU2 black-box
  - SCID inverse design

Aerodynamic wing design/optimization: Historic trends



Wing Design Approach: a *procedure*

Sequential approach (break into sequence smaller steps)

Planform: given

1) Iterate

Determine *thickness* distribution:

- Min. Wave drag,
  - maintaining wing box capacity

Determine *camber & twist* (combined):

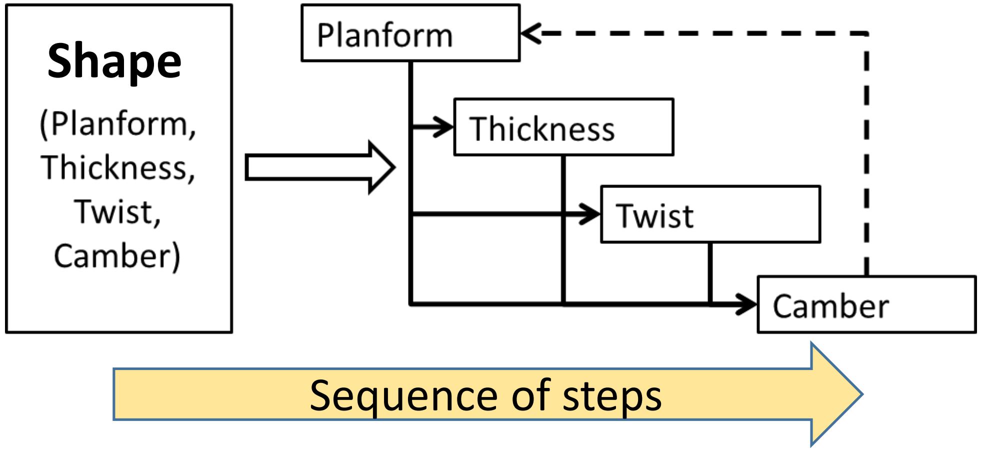
- Min. Induced drag
  - Check: ▪ Span loading shape
    ▪ Root bending moment (RBM)

2) If winglet: optimize cant/fold angle, etc.
   - reduce drag or improve RBM

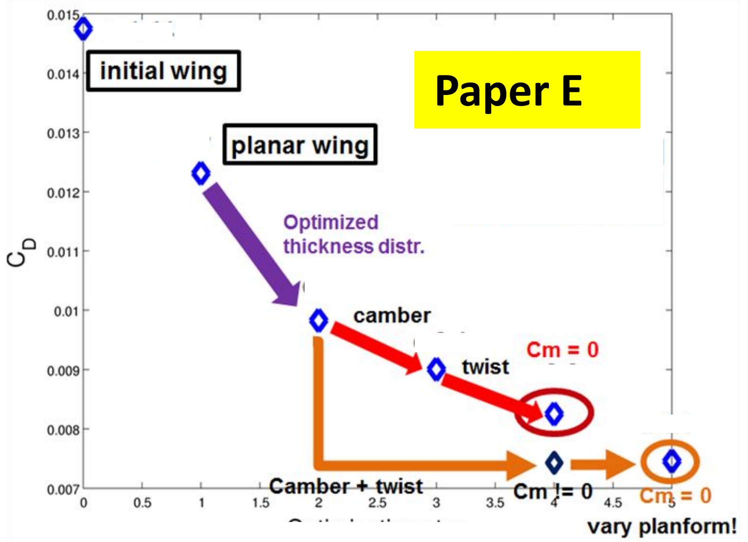
3) Engineering know-how (applied at ◊)

Swept isobars, span loading, thickness tapering, Area ruling, tip wash, etc

NOT an algorithm



Way it works



User interaction

Wing design optimization – 3 optimizer combinations

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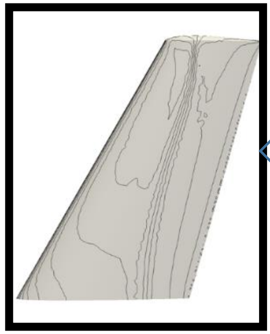
Engineer interaction
- "baseline" shape
- target C^*_p
- geometry constraints,…

INVERSE SOLVER
SCID

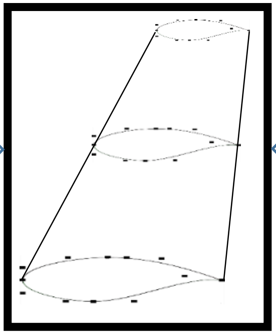
Surface Curvature Inverse Design

- Find geometry yielding target C^*_p
- Euler, RANS: $\min_{shape,AoA} \left\| C_p - C_p^* \right\| \ \text{s.t.} \max(t/c) \geq a_1, \ldots$
- Enables isobar "tailoring" at root and wing tip
- Use locally to improve pressure distribution
- Maps *shape* to *flow* C_p

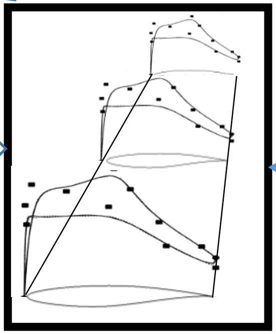
Geometry smoother/ Grid generator *sumo*



Working design Cp



Working design Geometry



Target Cp*

User Interactive *Target Pressure Editor*

Engineer interaction limited to:
- "baseline" shape
- objective function
- constraints,…

SU2
All-in-box

Integrated design system

Direct Optimization

Minimize C_D or L/D or …

$$\min_{shape,AoA} C_D \ \text{s.t.} C_L \geq a, |C_m| \leq b, \max(t/c) \geq a_1, \ldots$$

- **Tightly coupled** - used as integrated closed system
- Parameters determine shape perturbation & mesh deformation
- Shape defined by **many parameters**
- **Baseline mesh from CPACS/sumo**
- Built-in optimizer uses gradient from adjoint solution

CEASIOM-OPT

$\frac{\partial(\cdot)}{\partial p_j}$ SQP Matlab

sequential approach to shape opt

Shape defined by ***a few parameters*** *p1,p2,…*
min (*p1,p2,…*) $J(C_L, C_D, \ldots)$
s.t. $Cons(C_L, C_D, \ldots) <= 0$

- **Loosely coupled** to flow solver, grid generator, etc
- Parametric shape definition & re-meshing
- Allows sequential treatment twist, thickness, camber, etc
- Flexible choice of objective function & constraints, …
- Offers easy & plentiful Engineer interaction

4. Results and discussion of selected design studies

- Comparing 2 direction optimization methods: *ONERA M6 wing*
- Sequential optimization procedure: *MOB blended wing body*
- Inverse transonic wing design: *joined wing configuration*
- Propeller slipstream model Euler: *Twin-prop 16 seater*
- Control surfaces modelling in CEASIOM: *Piaggio Avanti*
- Flight motion analysis, data fusion: *Transonic Trans-Cruiser*

5. Conclusions

Engineering Solutions and Innovations

- CEASIOM software improved
  - Wing design toolbox: 2 direct opt methods, 1 inverse design
    - Loosely coupled direct optimization
    - Tightly coupled direct optimization
    - Inverse design
  - Generalization of CEASIOM
    - airframe geometry modeling
    - Import function
    - CPACS dataset
  - Demonstrated effectiveness on number of applications
    - Conventional as well as unconventional concepts
      - BWB Inviscid drag is reduced around 45% at desired lift with fixed planform
    - Transonic and low speed
    - Used to assess flying qualities
- Lessons learned
  - CEASIOM applied to the various design loops
  - Wing design is a *procedure* – therefore “cocktail mix” of opt methods is good strategy
    - Engineer drive the process
    - Less tedious, better user interface, recommendation settings, …
    - Optimization with re-meshing technique robust
  - Limitations of data fusion
    - Utilize DACE Toolbox, construct the meta-modelling procedures
  - Optimization with re-meshing technique robust

6. Future work

- CEASIOM works better with CPACS
  - Enhance CEASIOM capabilities in MDO
    - Better W&B module for flight simulation
    - Better configuration modelling by adopting CPACS: CPACScreator
  - Each individual module works with CPACS
    - CPACScreator → CPACS
    - Sumo → CPACS
    - Tornado → CPACS (on progress)
    - …
  - Each individual module integrated into RCE