Loads Analysis and Structural Optimization - A Parameterized and Integrated Process

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AE: Institute for Aeroelasticity
BT: Institute of Structures and Design
FA: Institute of Composite Structures and Adaptive Systems
SR: Institute of System Dynamics and Control

DLR

Motivation and Approach

Motivation:

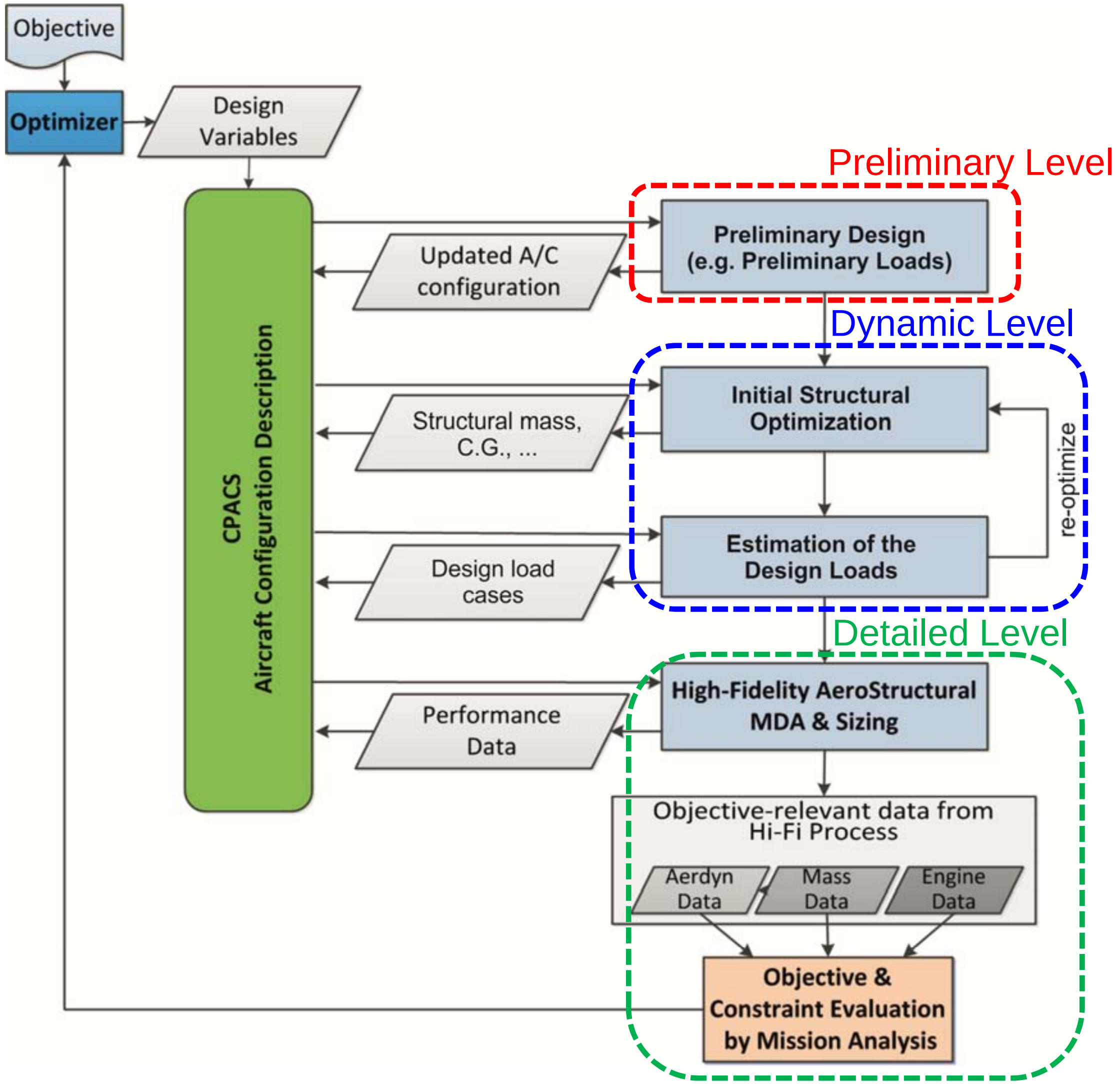
- Determination of configuration specific design load cases for hi-fi aero/structural design
- Integration of a comprehensive loads process in the early aircraft design
- Automated loads and structural optimization process for aircraft MDO

Approach:

- Parametric modeling of all simulation and optimization models
- Load case definition with consideration requirements from regulations
- Loads analysis
  - Static manoeuver loads analysis (with and without flight control system)
  - Dynamic gust loads analysis (with and without flight control system)
- Structural optimization with aeroelastic constraints (aileron reversal)
- Delivery of design loads and availability of structural design properties

Exemplary Overall Design Process - DLR Project Digital-X

- Overall design loop for optimization of an aircraft configuration, set up within the DLR project Digital-X
- Three-step approach:
  - Preliminary level
  - Dynamic level
  - Detailed level
- Focus of the presentation:
  - Dynamic level
  - Only structural design aspects of the detailed level



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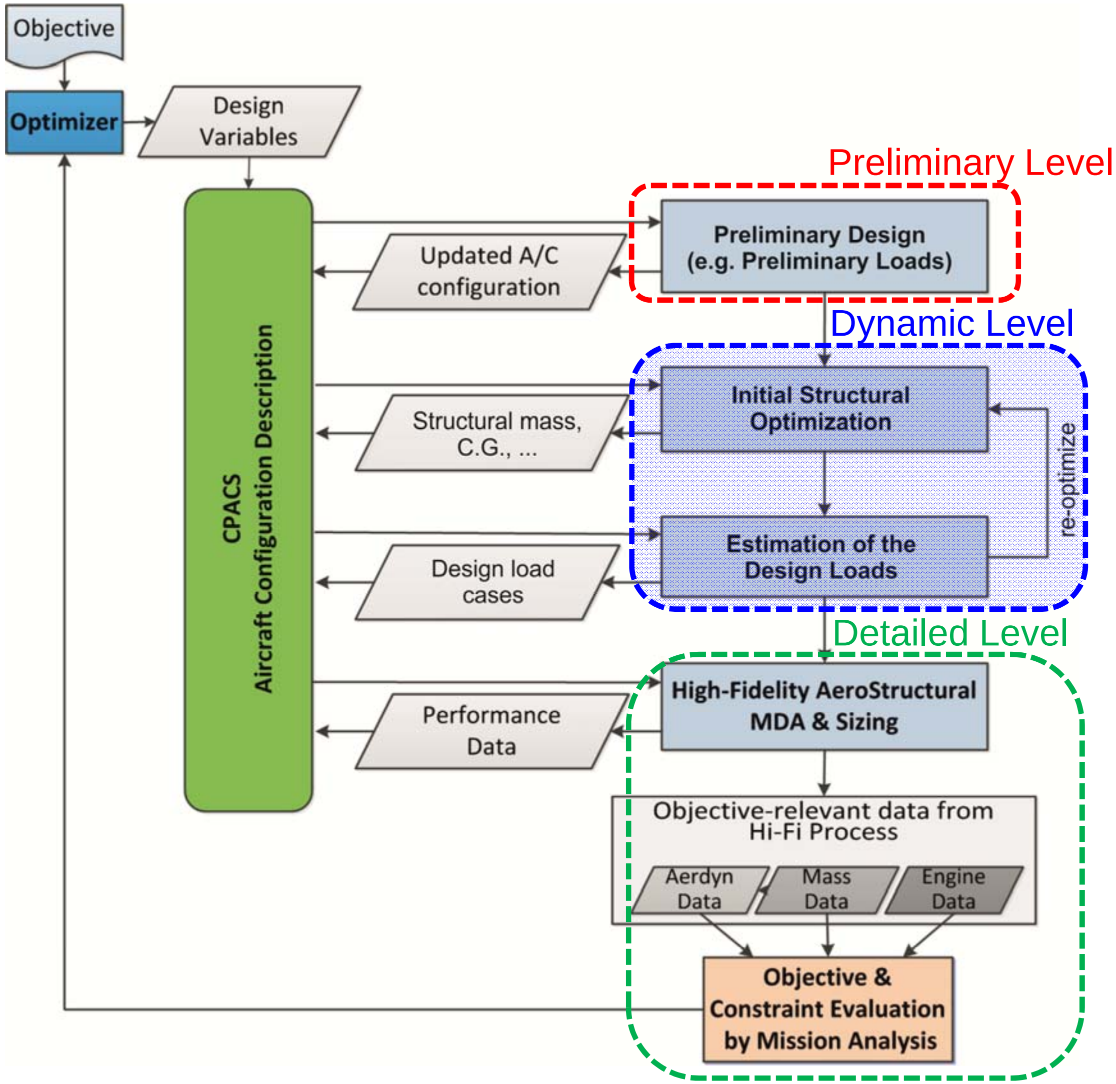
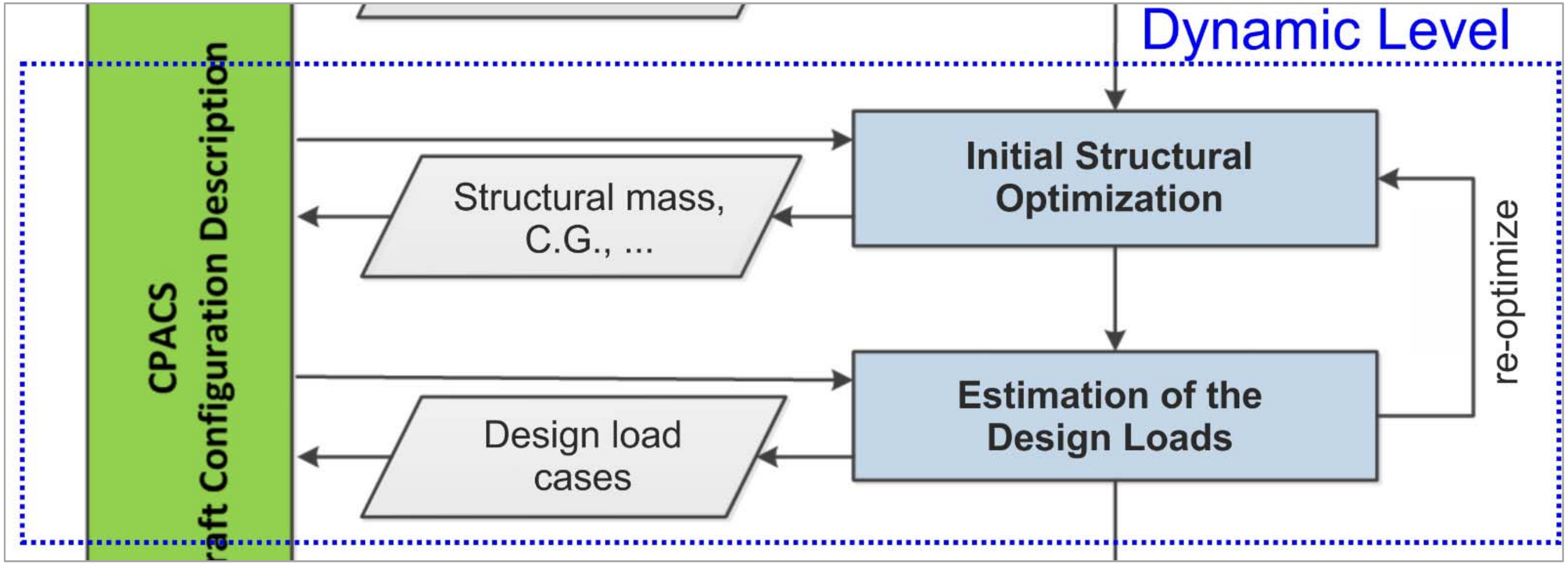


Load Analysis and Structural Optimization Process



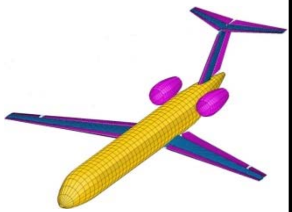
- Process part of overall A/C MDO process (e.g. Digital X), but also stand alone
- Subsequent explanation shows the capabilities of the process
- Finally special emphasis on loads analysis with flight control system (e.g. for maneuver load and gust load alleviation)

Loads Analysis and Structural Optimization Process

Start

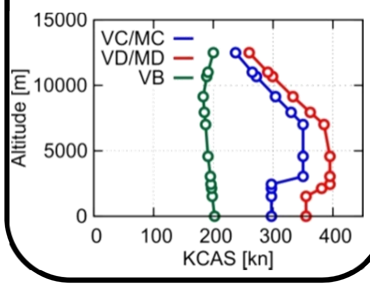
Model Set-up

- Parametric approach
- CPACS interface
- All „models“ of the process are covered



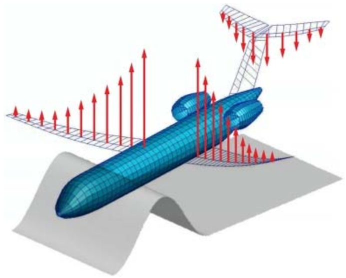
Load case definition

- Mass configurations (fuel, cargo, passenger)
- Design speeds
- Flight envelope (altitude, Ma)
- CS 25.341



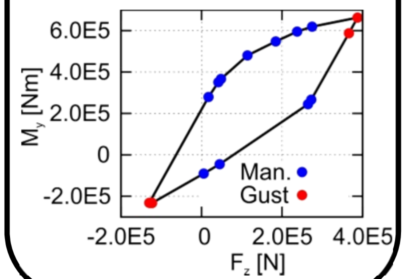
Loads analysis

- Maneuver
- Gust
- Continuous turbulence
- Ground/Landing
- Special load cases



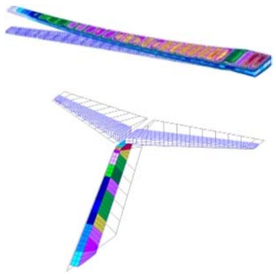
Loads post processing

- Balanced loads
- Loads database
- Sorting and filtering of loads
- Nodal and cutting loads



Structural Optimization

- Gradient-based optimization
- Various optimization models



Conv.?

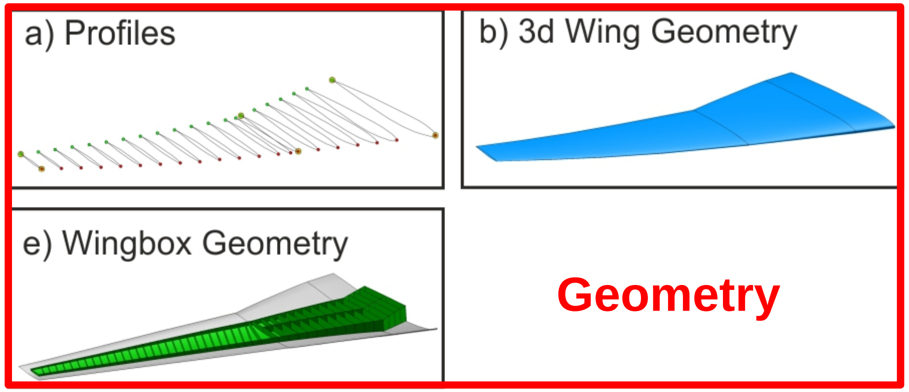
No

Convergence of structural mass and loads

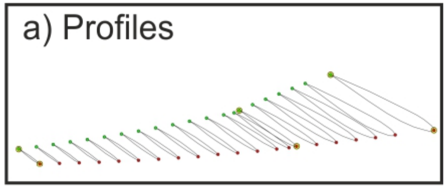
End

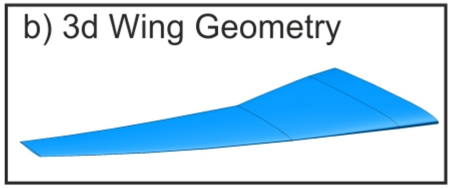
Parametric Modelling Concept – Full Model

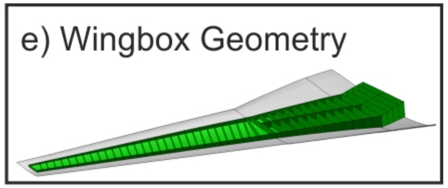
Parametric Modelling Concept – Full Model

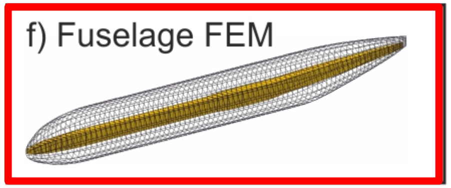


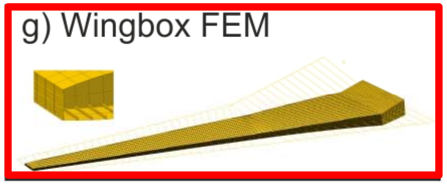
Parametric Modelling Concept – Full Model







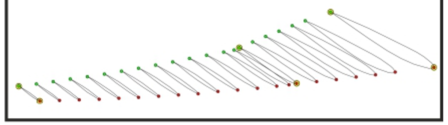




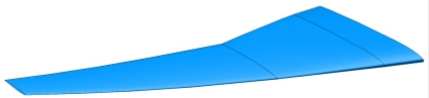
Loads Carrying Structure

Parametric Modelling Concept – Full Model

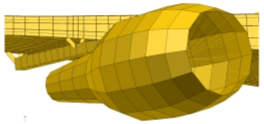
a) Profiles



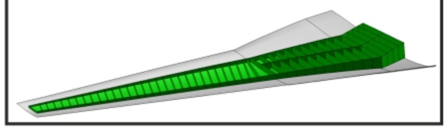
b) 3d Wing Geometry



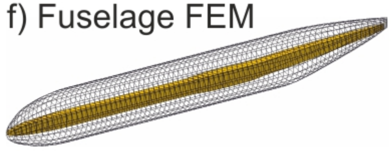
d) Engine / Pylon Model



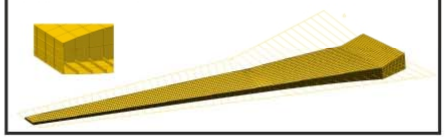
e) Wingbox Geometry



f) Fuselage FEM



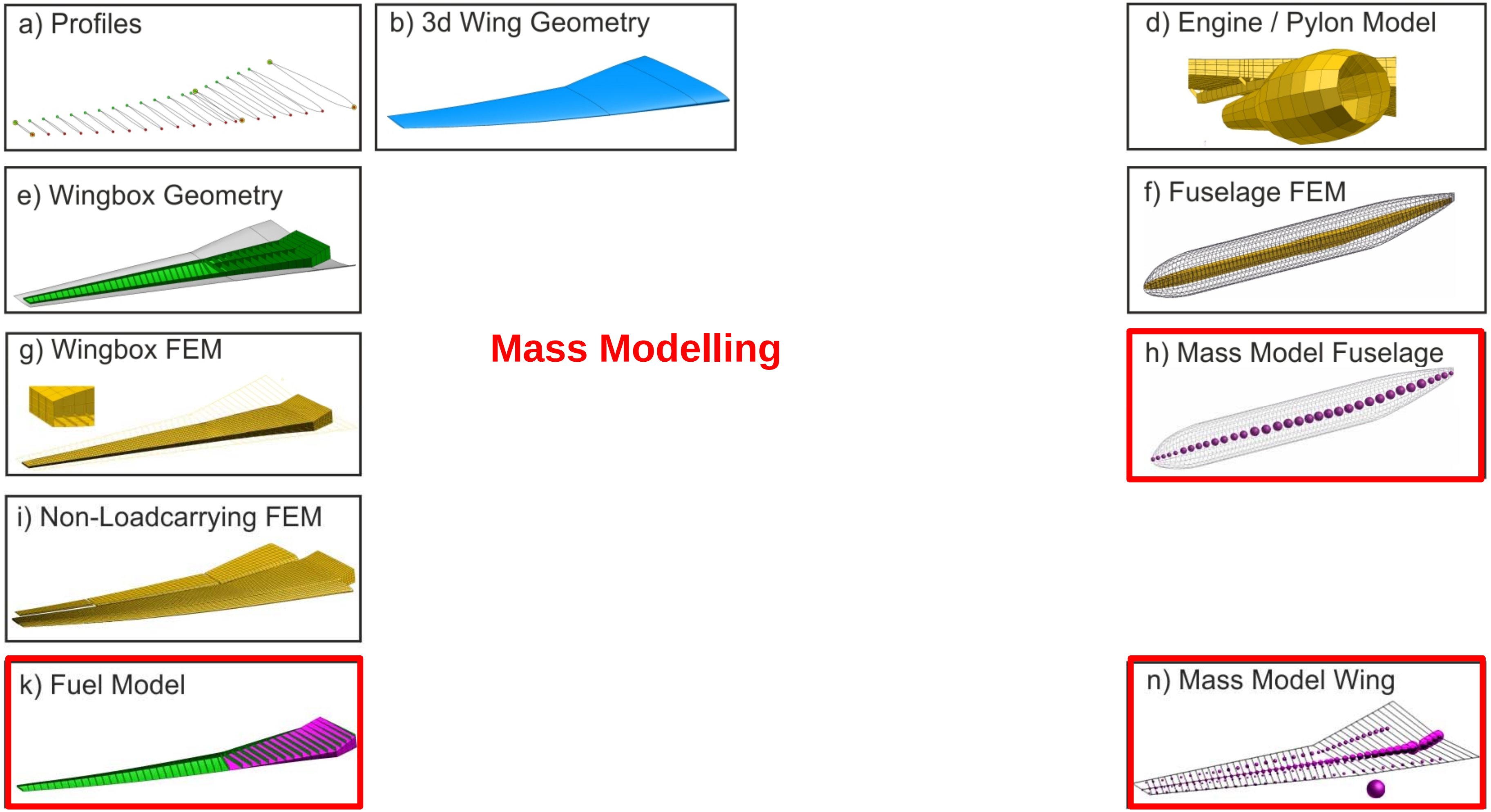
g) Wingbox FEM



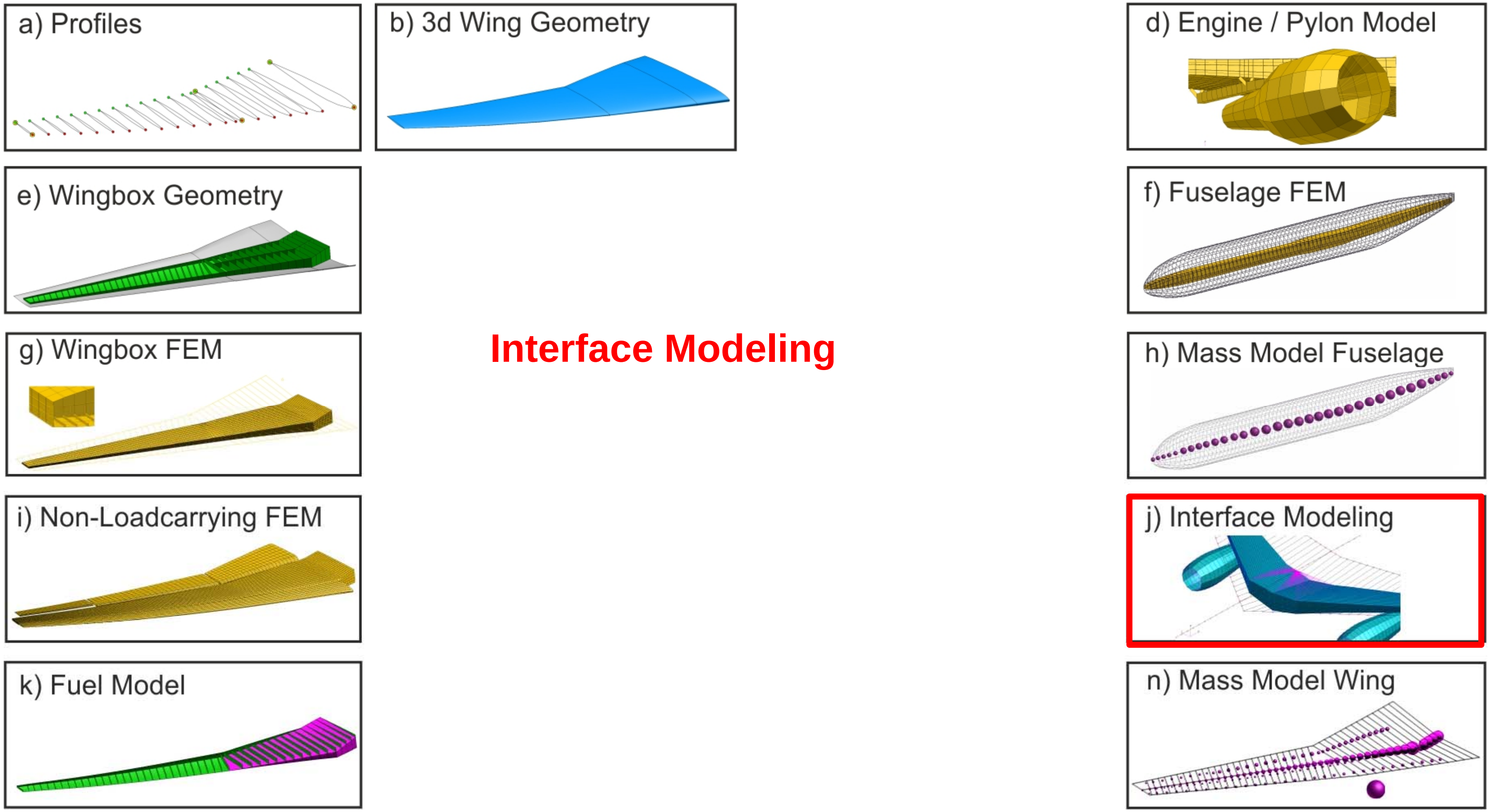
- Secondary Structure
- Non-Load Carrying Structure
- Other Structure

i) Non-Loadcarrying FEM

Parametric Modelling Concept – Full Model

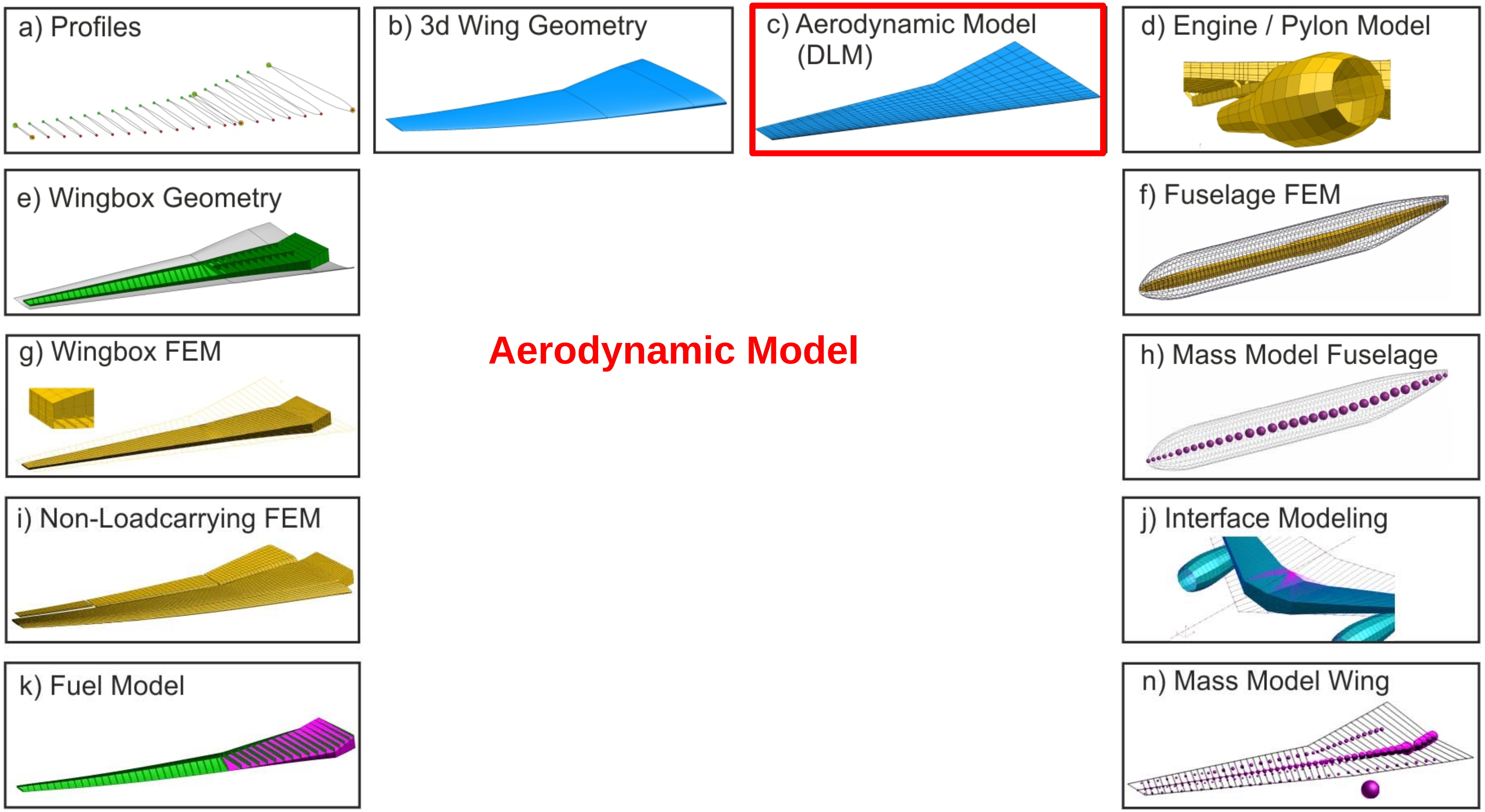


Parametric Modelling Concept – Full Model

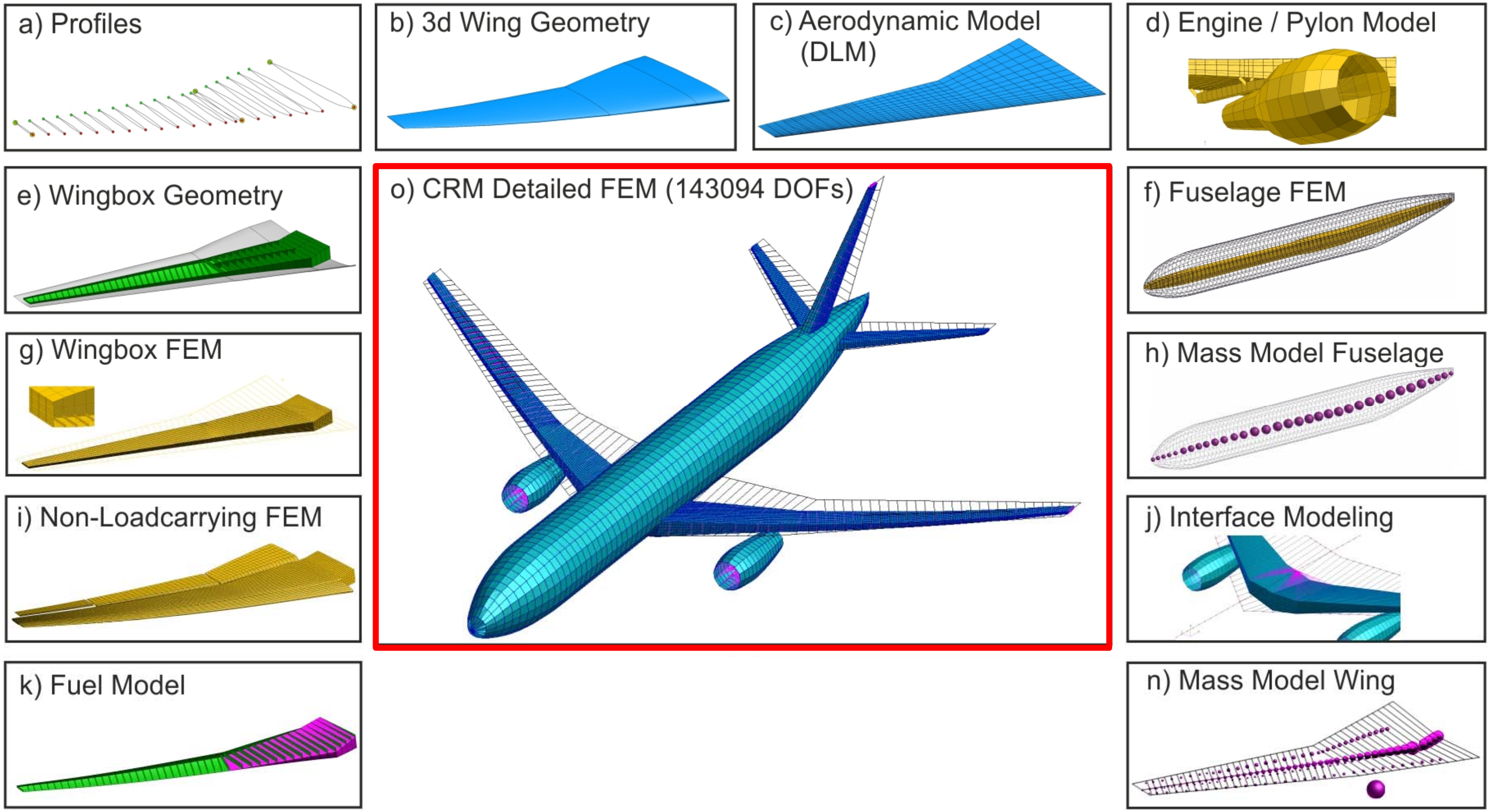


DLR

Parametric Modelling Concept – Full Model



Parametric Modelling Concept – Full Model



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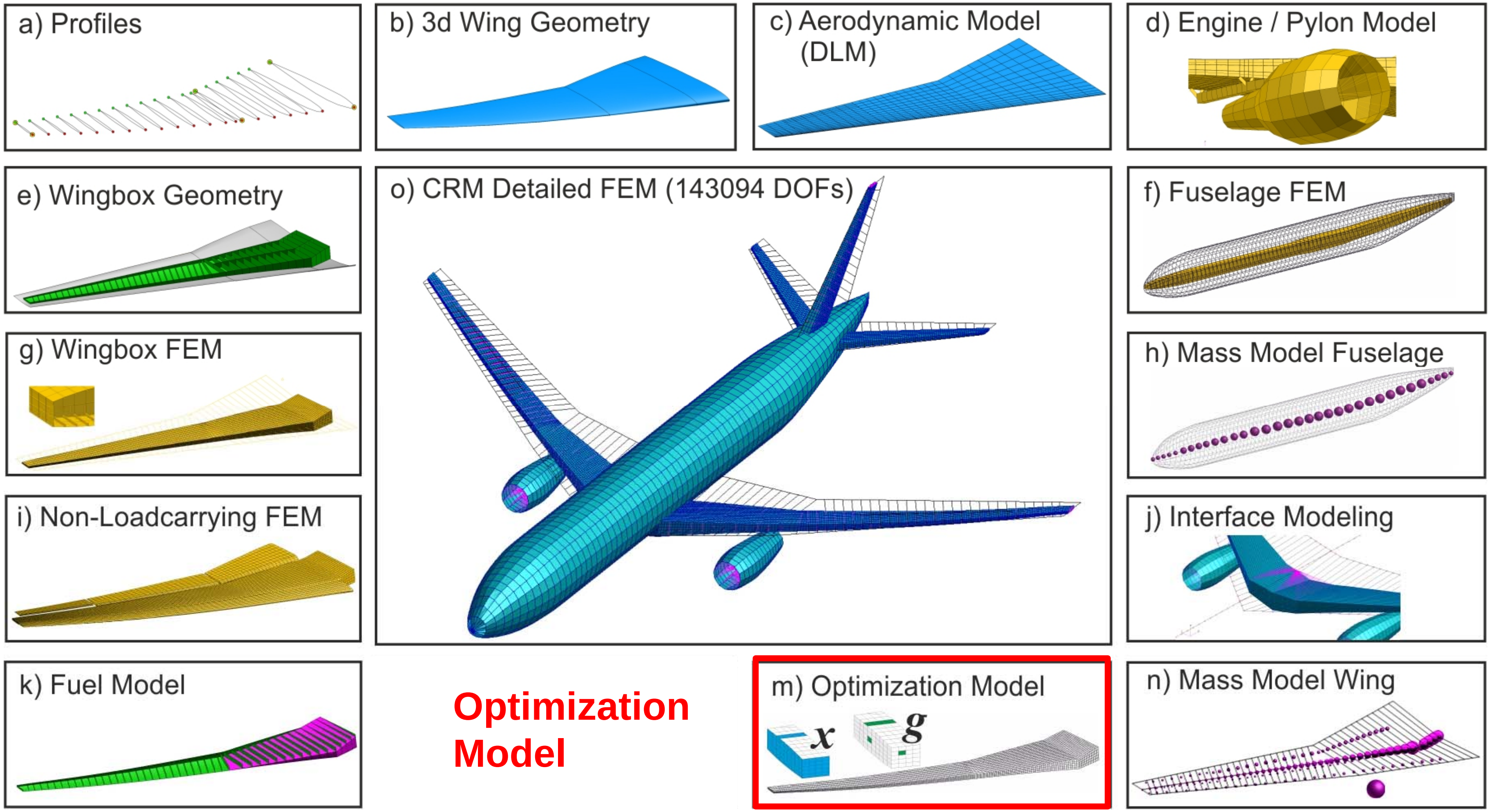
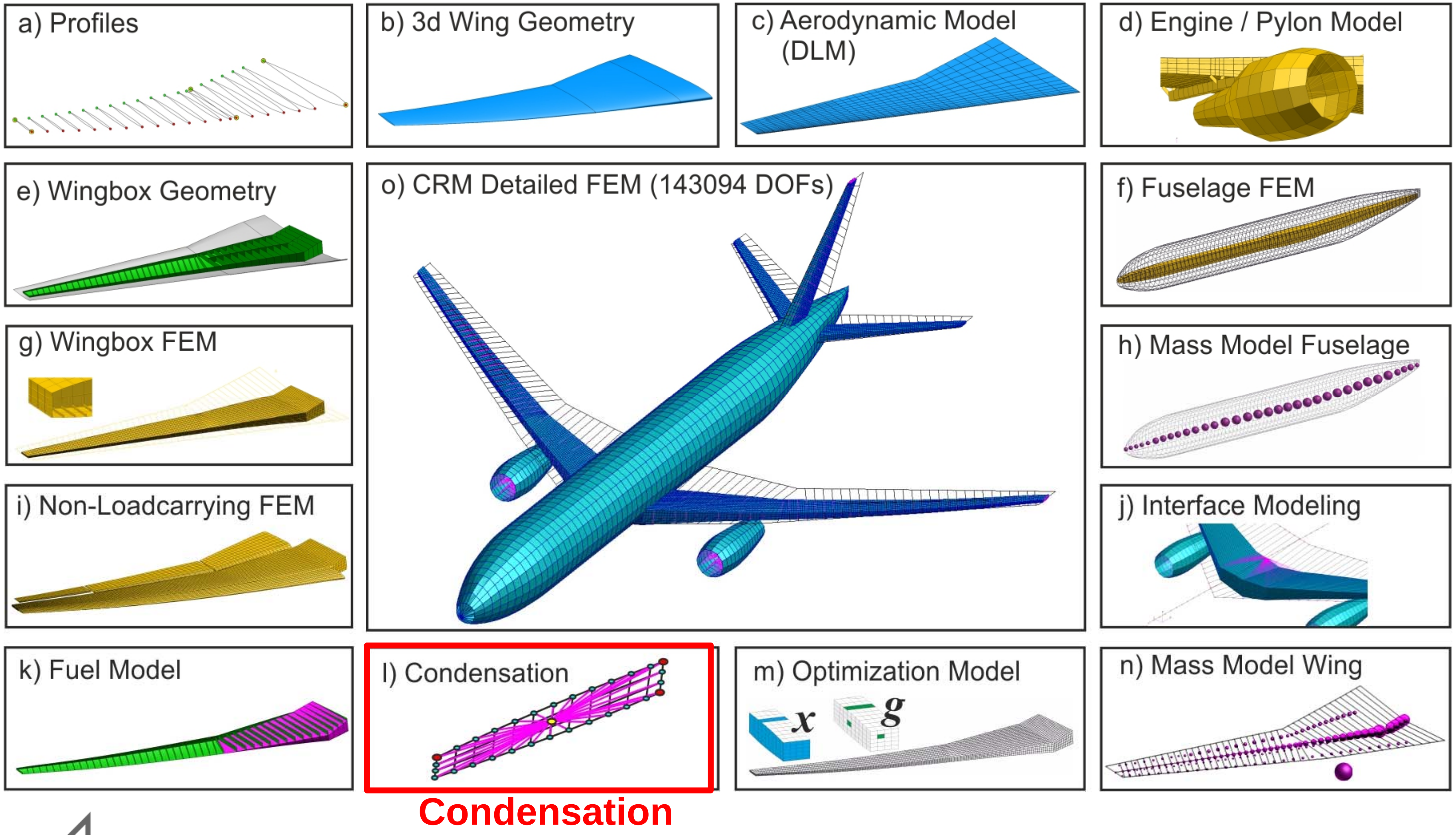
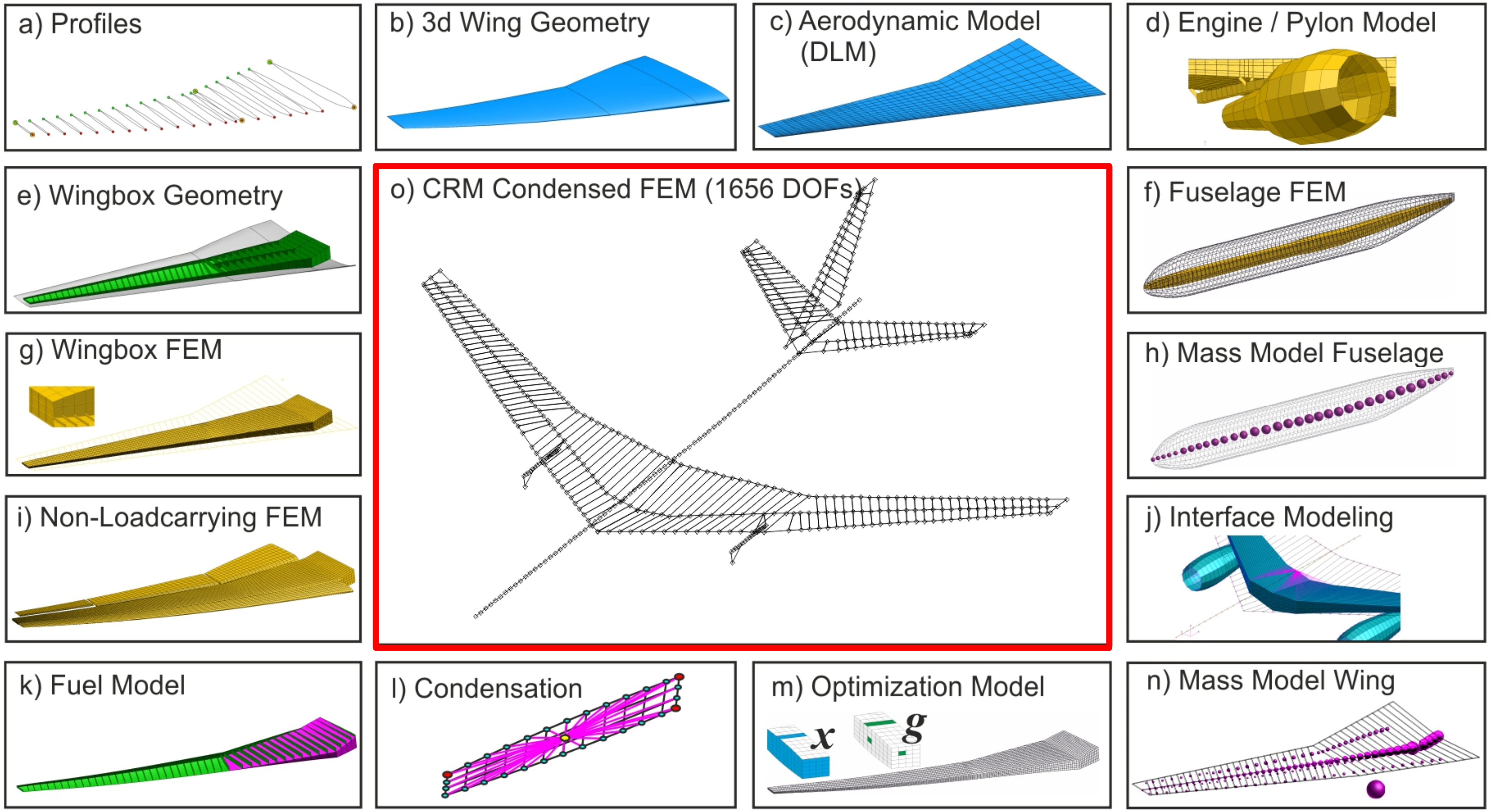


Parametric Modelling Concept – Full Model



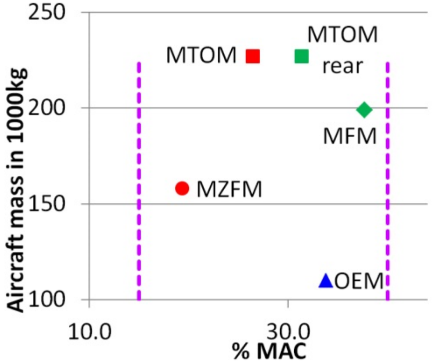
Parametric Modelling Concept – Condensed Model



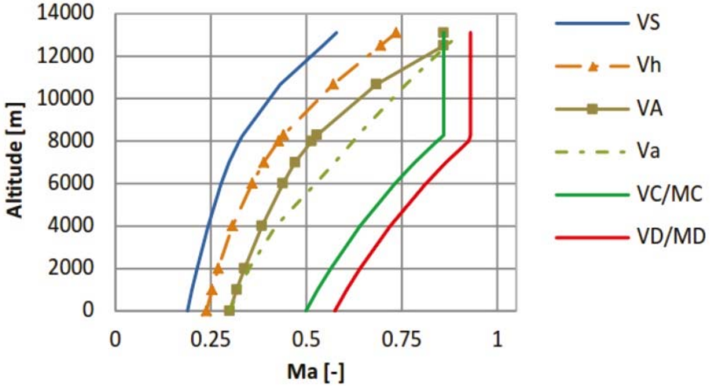
Load Assumption – Load Case Definition for DLR-XRF1

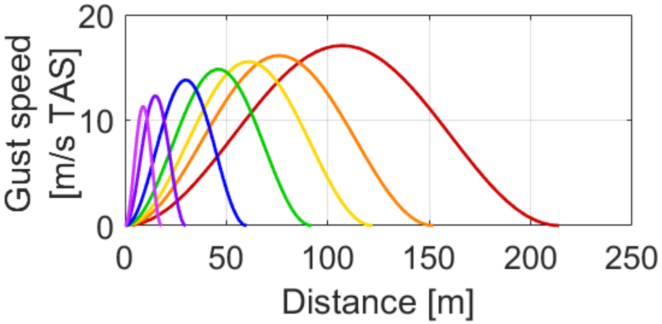
Parameter	Nb.	Remarks
Mass configurations	9	From OEM to MTOM
Flight levels	6	0 to 13100 m
Design speeds	6	VS, Vh, VA, Va, VC/MC, VD/MD
Stationary trim manoeuvers	9	Sym. pull-up, push down, yawing, rolling)
Gust gradients	10	9 - 107 m
Gust directions	4	Vertical up and down Horizontal left and right
Elastic modes	Var.	up to 40 Hz

Load cases definition in line with corresponding paragraphs of CS25



Total Nb. of Load Cases: 9*6*6*(9+4*10) = 15876





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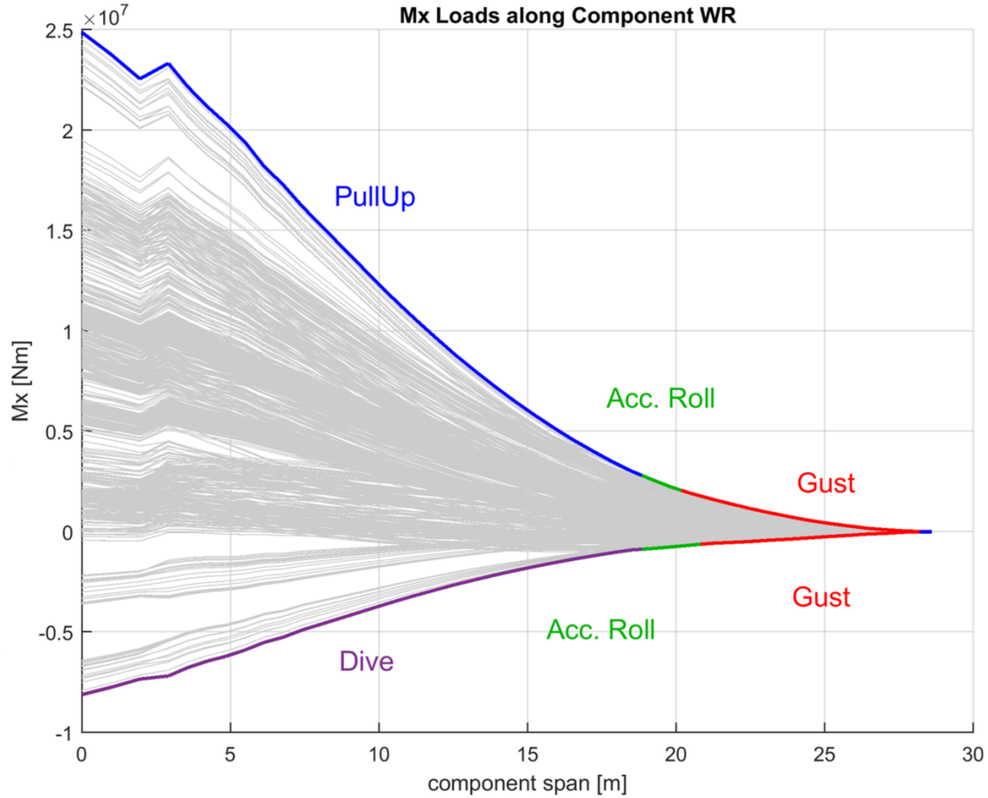
Design Load Selection for DLR-XRF1

Cut load envelopes for each aircraft component:

- shear force
- torque moment
- bending moment



Design Loads:
max & min cut forces/moments for each cut station and each degree of freedom

Wing Bending Moment (Mx):

- Pull Up & Push Down up to 2/3 span
- Accelerated Roll and Gust in last 1/3 span
- Dominant cases:
  - o Max. take off mass
  - o cruise and diving speed
  - o max. flight altitude

Structural Optimization - Capabilities

Maximum…
Nb. of Design Variables: ~1000
Nb. of Constraints: ~ 10^6

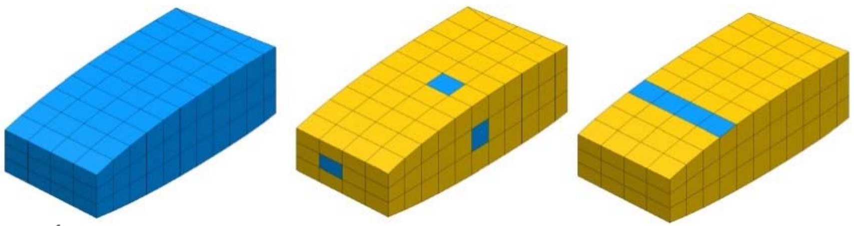
Mathematical formulation of the optimization problem

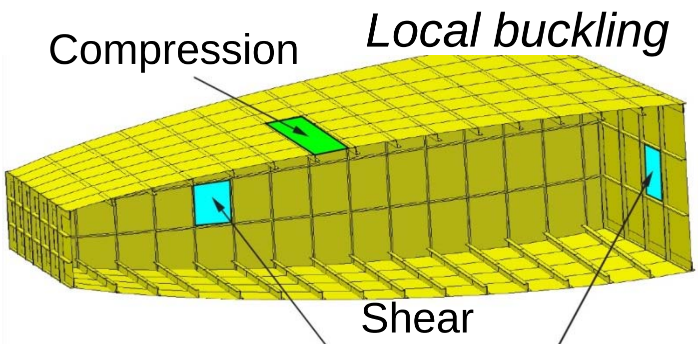
$$Min\ \{f(\boldsymbol{x})|\boldsymbol{g}_j(\boldsymbol{x}) \geq 0; \boldsymbol{h}_k(\boldsymbol{x}) = 0, j = 1, \dots, p, k = 1, \dots, q\}$$

Objective f:	Structural mass of the load carrying structure
Design variables $\boldsymbol{x}$:	Thickness t of the shell elements Lamination parameter for CFRP-Material
Inequality constraints $\boldsymbol{g}(\boldsymbol{x})$:	Element stress, strain, buckling (handbook formula) Aileron efficiency, divergence dynamic pressure
Equality constraints $\boldsymbol{h}(\boldsymbol{x})$:	None.

Application of gradient based optimization algorithms (e.g. MSC Nastran)

Design Variable Models

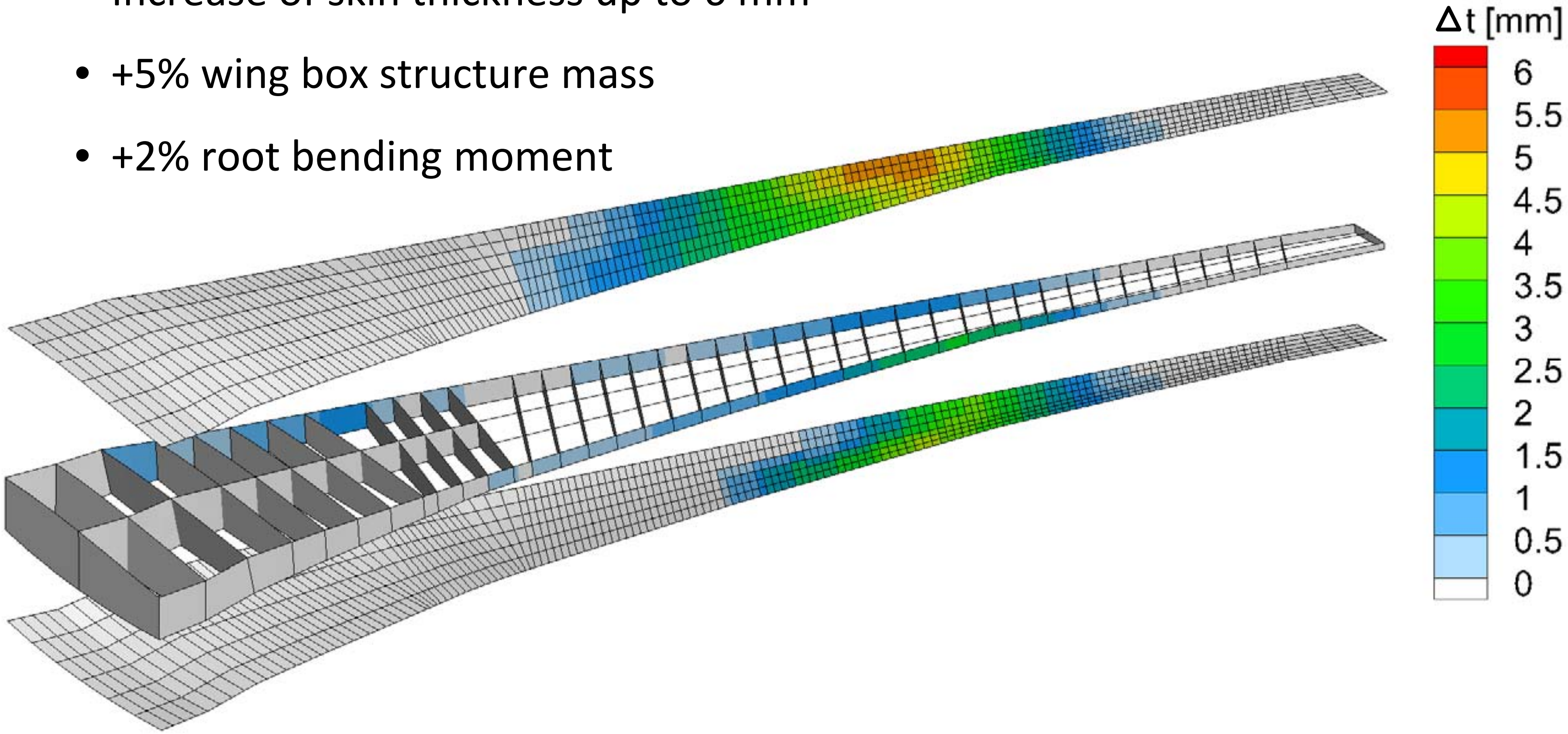




Example: Additional Skin Thickness due to Aileron Effectiveness Constraint – DLR-XRF1

With aileron reversal constraint sizing included:

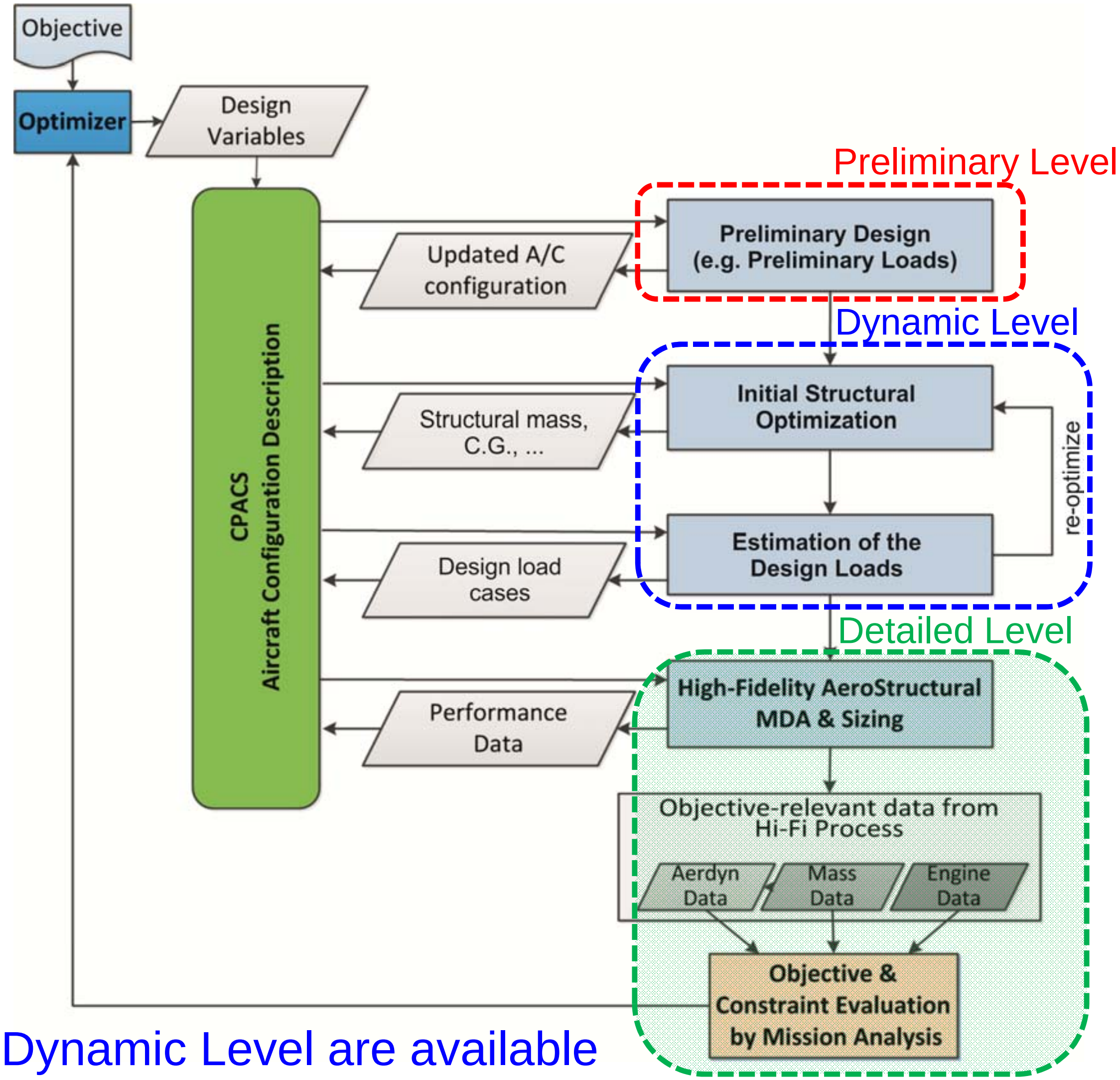
- Increase of skin thickness up to 6 mm
- +5% wing box structure mass
- +2% root bending moment



DLR

Exemplary Overall Design Process - DLR Project Digital-X

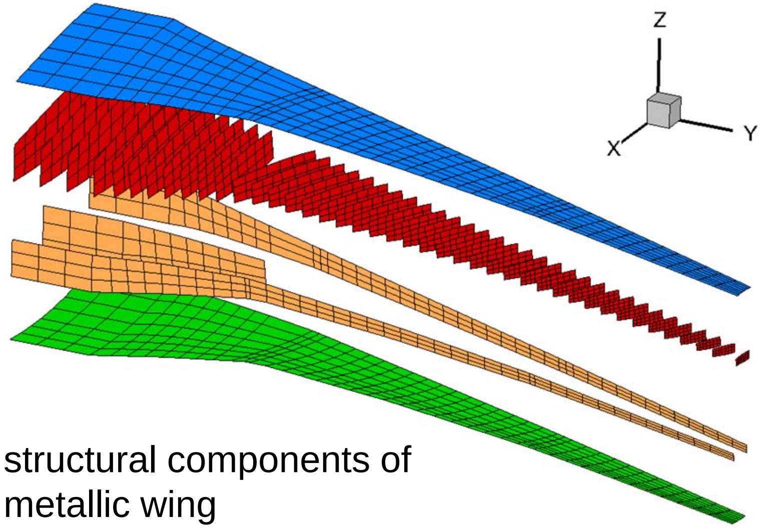
- Overall design loop for optimization of an aircraft configuration, set up within the DLR project Digital-X
- Three-step approach:
  - Preliminary level
  - Dynamic level
  - Detailed level
- Focus of the presentation:
  - Dynamic level
  - **Only structural design aspects of the detailed level (DLR-FA, DLR-BT)**
- Dynamic Level delivers loads to Detailed Level
- Structural design properties of Dynamic Level are available



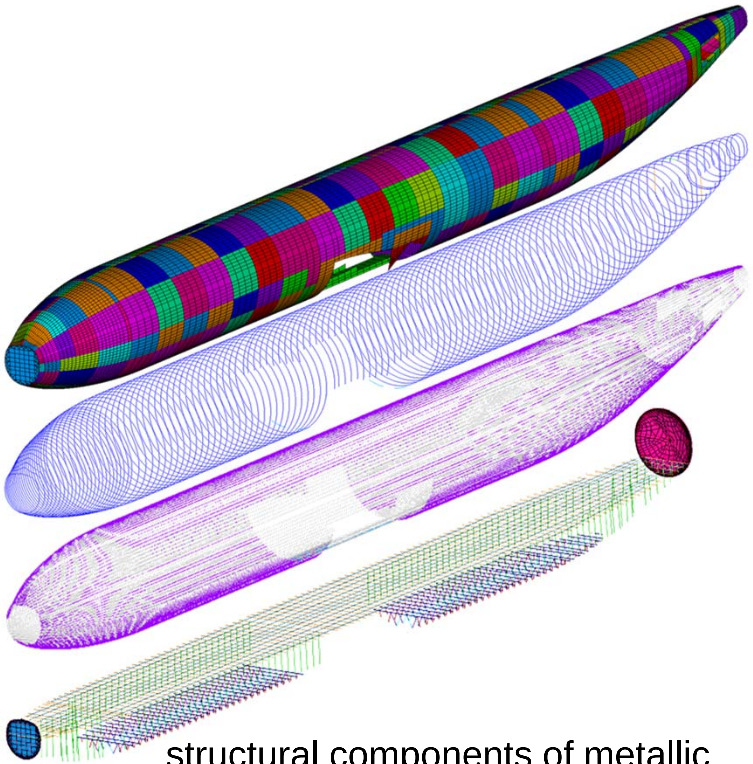
DLR

Structural Model Generators

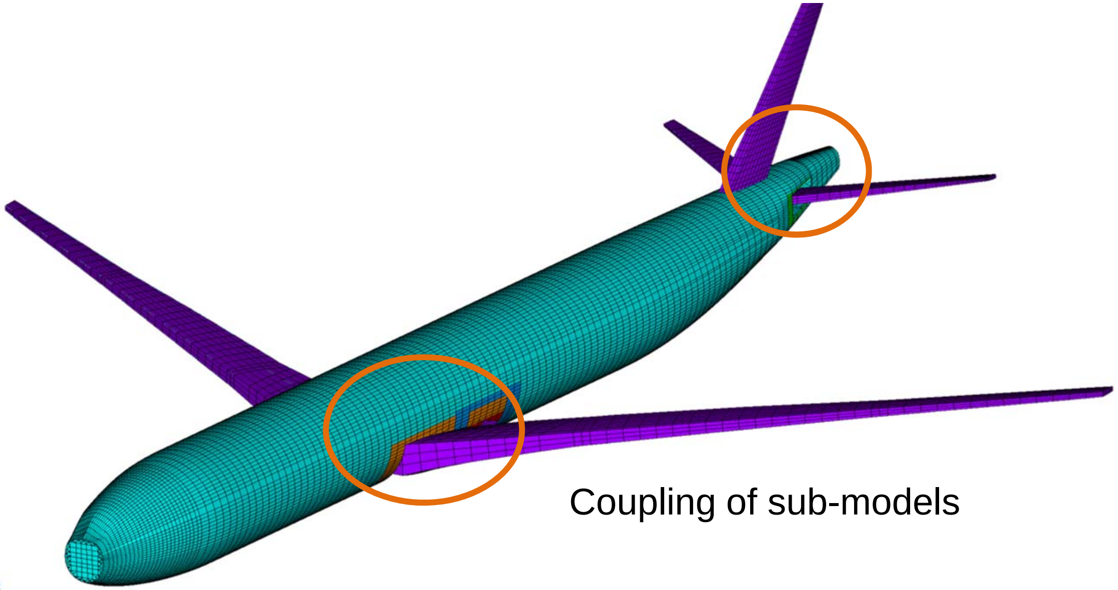
- Parameterized fuselage and wing models based on CPACS input
- Fully automated coupling of sub-models using consolidated interfaces



structural components of metallic wing

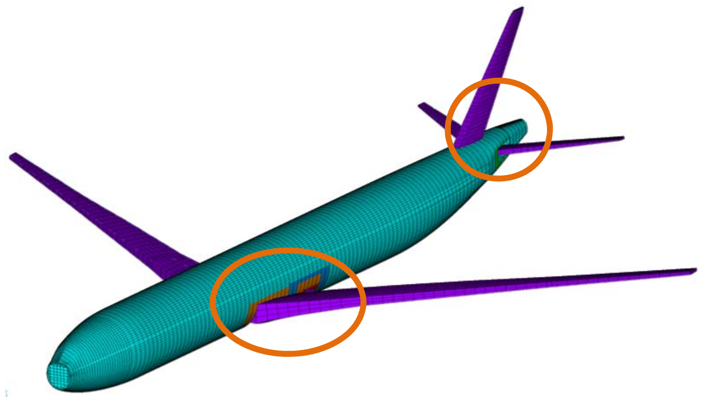


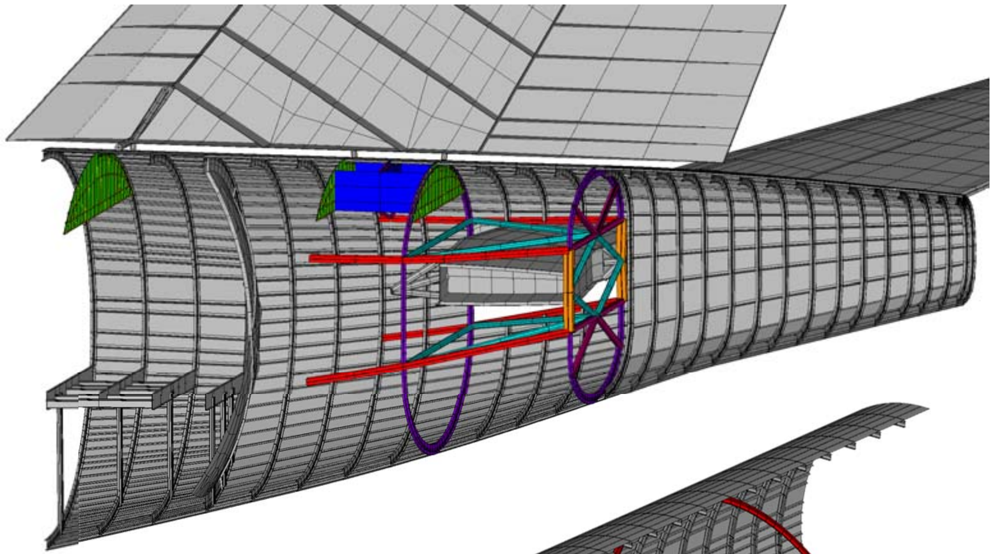
structural components of metallic fuselage

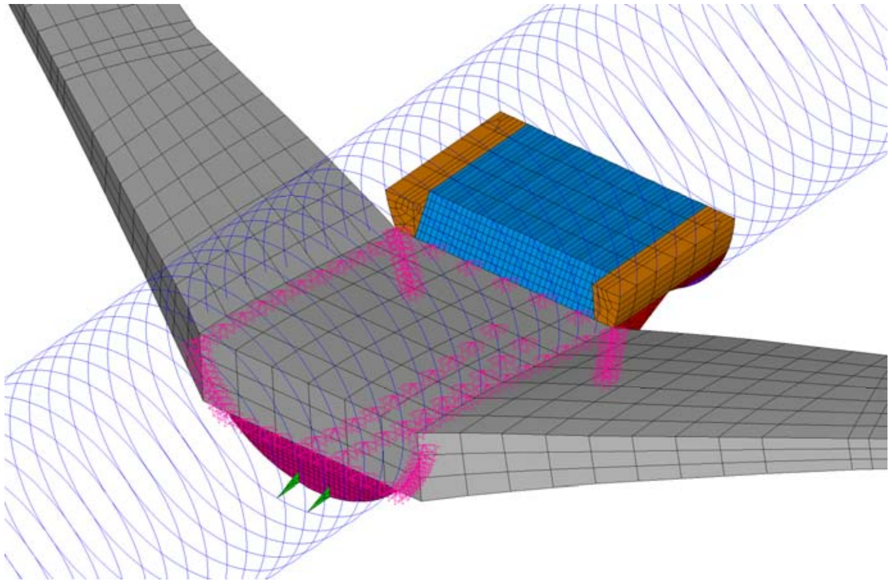


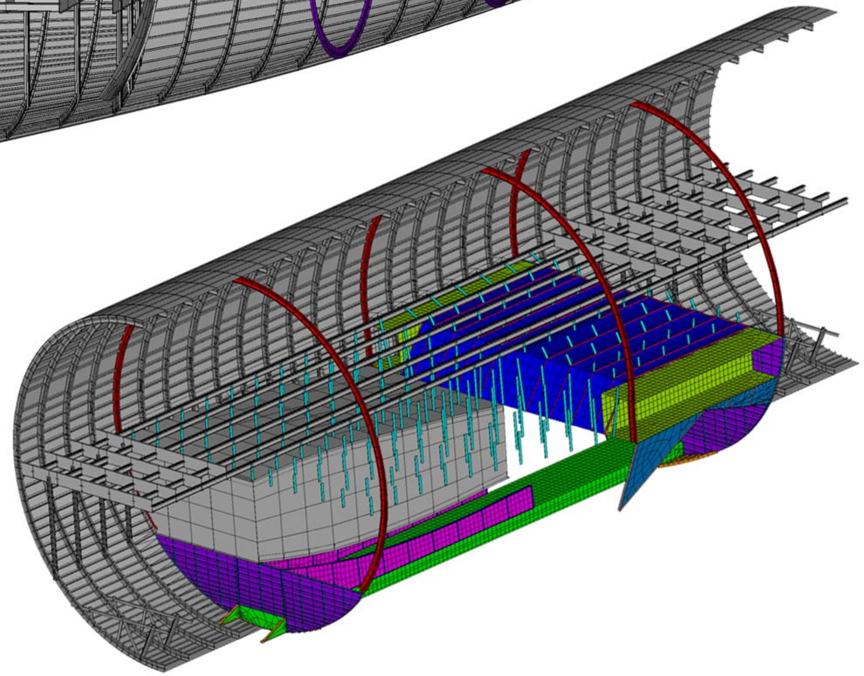
Coupling of sub-models

Coupling of Fuselage and Wing Models

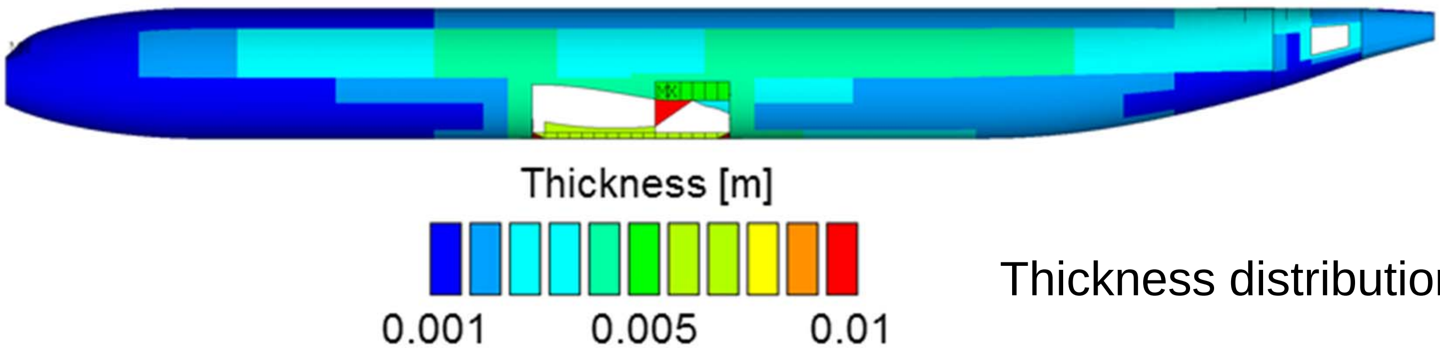




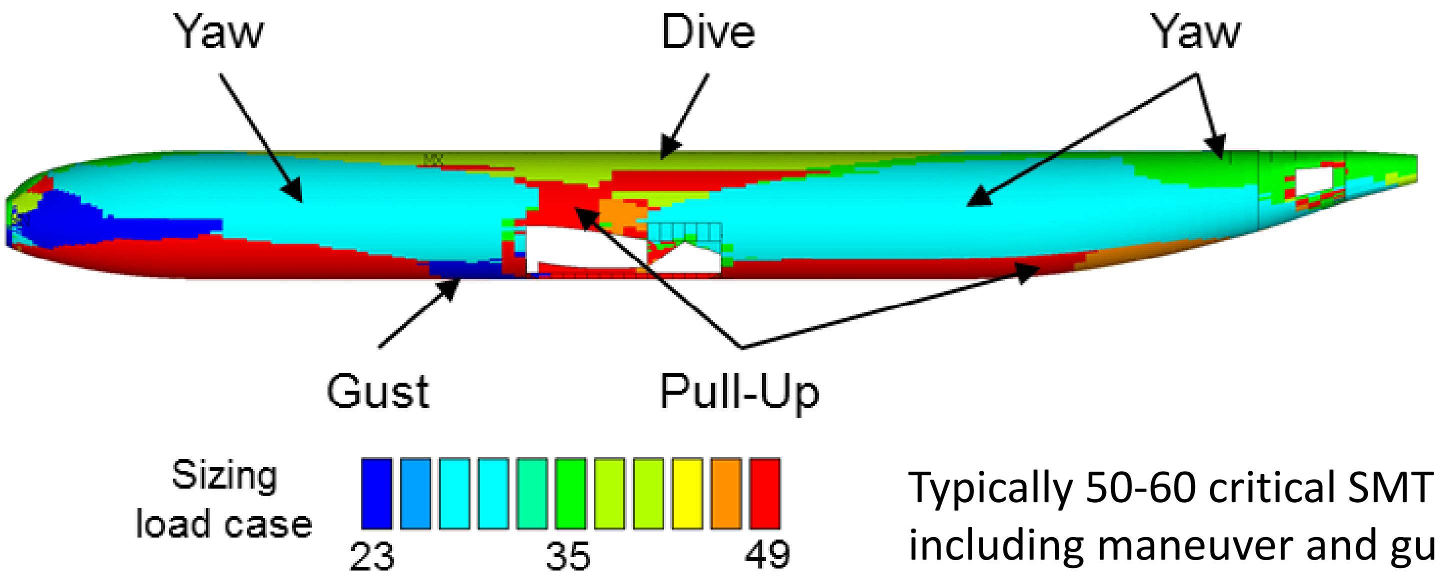




Static Structural Sizing - Results

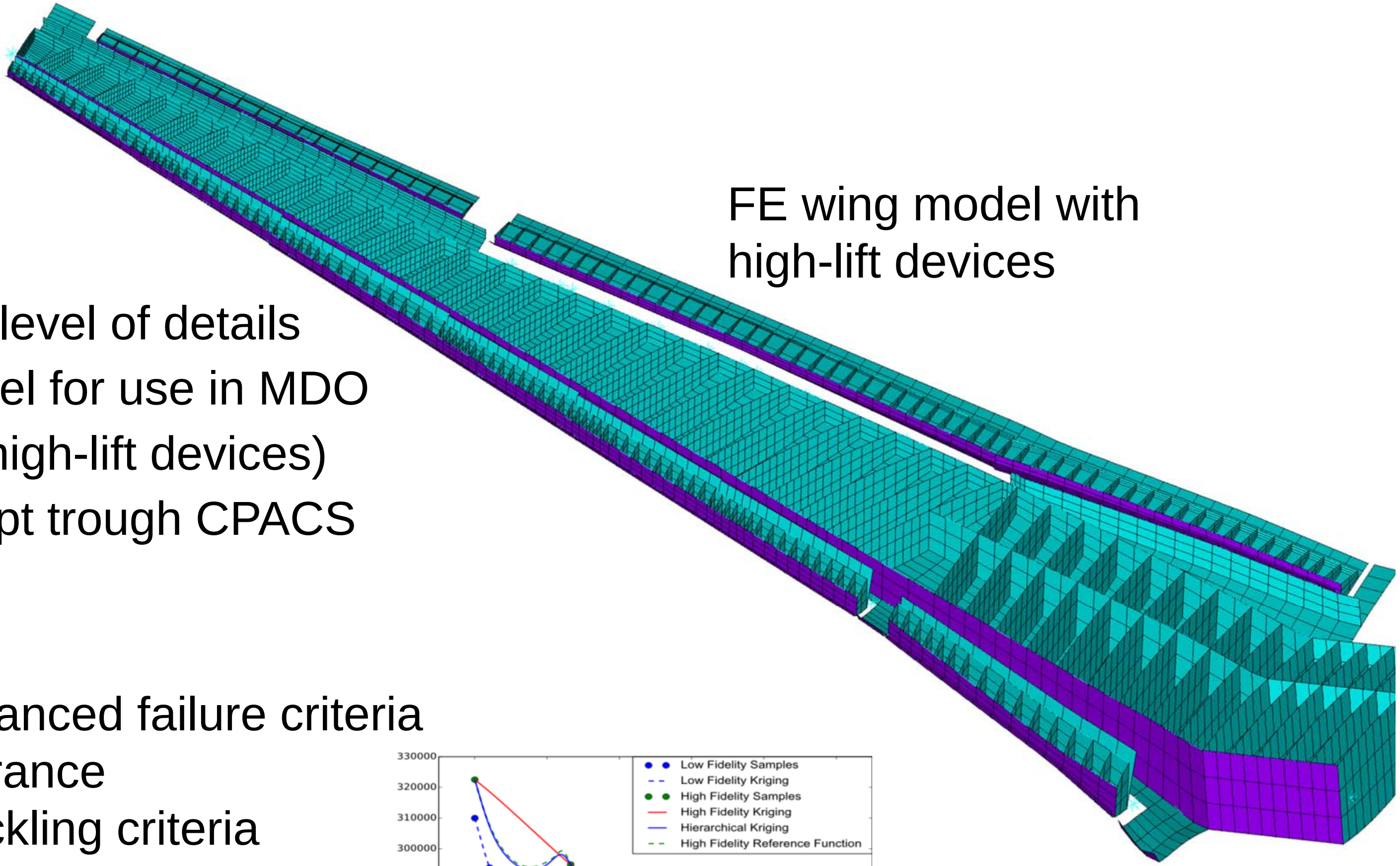


Thickness distribution



Typically 50-60 critical SMT load cases including maneuver and gust loads

Detailed Structural Design (outlook)

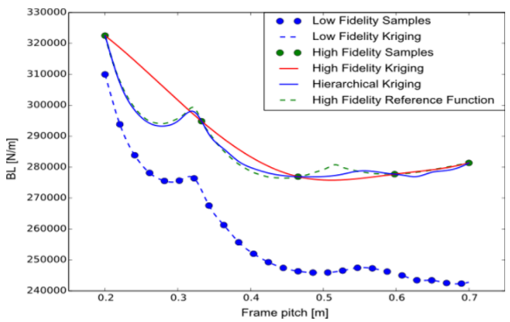


FE wing model with high-lift devices

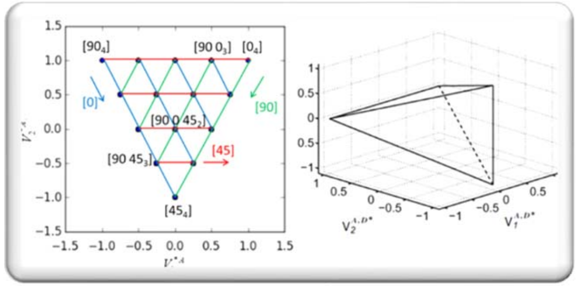
Further increase of level of details within FE wing model for use in MDO (e.g. integration of high-lift devices)

- Parametric concept trough CPACS integration

- Integration of enhanced failure criteria
  - Damage tolerance
  - Improved buckling criteria by hierarchical meta-models

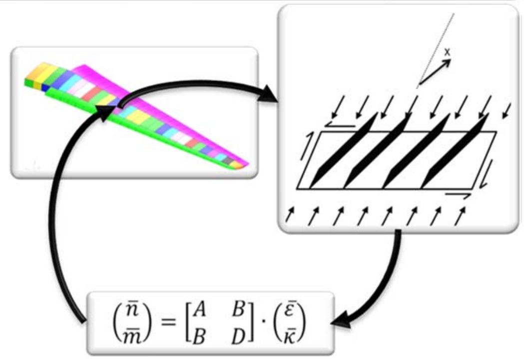


Detailed structural optimization of CFRP components



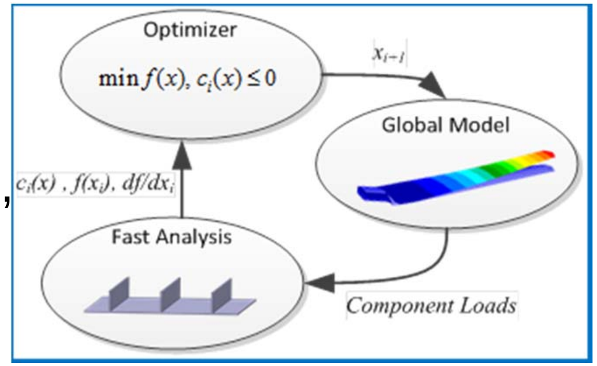
Efficient parametrization of composite panels

- Parametrization based on Lamination Parameters
  → *Continuous & convex design space formulation*
- Stringer stiffness smeared into panel representation
  → *design concept influence represented*
- Calculation of panel stiffness matrix parameters for FE-model coupling → *simplified FE-model*



Optimization process

- Global FE-model to calculate forces and displacements
- Object model with analytical panel representation
- Highly parallel, full gradient estimation
- lamination parameters transformed into layups



Optimization Constraints

- Static strength criteria (buckling, column buckling, strength, damage tolerance) & stiffness
- Consideration of manufacturing criteria (i.e. ply continuity) including gradient calculation

Summary and Outlook

- Parametric loads analysis and structural optimization process, working in different design and MDO environments, has a wide range of capabilities

- Extension of the structural optimization part (e.g. fatigue constraints)
- Extension of the loads analysis part (e.g. appropriate fatigue analysis, aero correction methods)
- Extension of the modelling part (e.g. fem of the fuselage for the Dynamic Level with same level of detail as the wings)
- Use of the loads and structural optimization process for gradient-based hi-fi aero-structural MDO
- Further development of interfacing with Detailed Level

- ***Loads analysis with closed-loop flight control system for maneuver- and gust load alleviation*** *presented by Thiemo Kier (DLR-SR)…*

Loads Analysis and Structural Optimization – Flight Control System Design as part of MDO

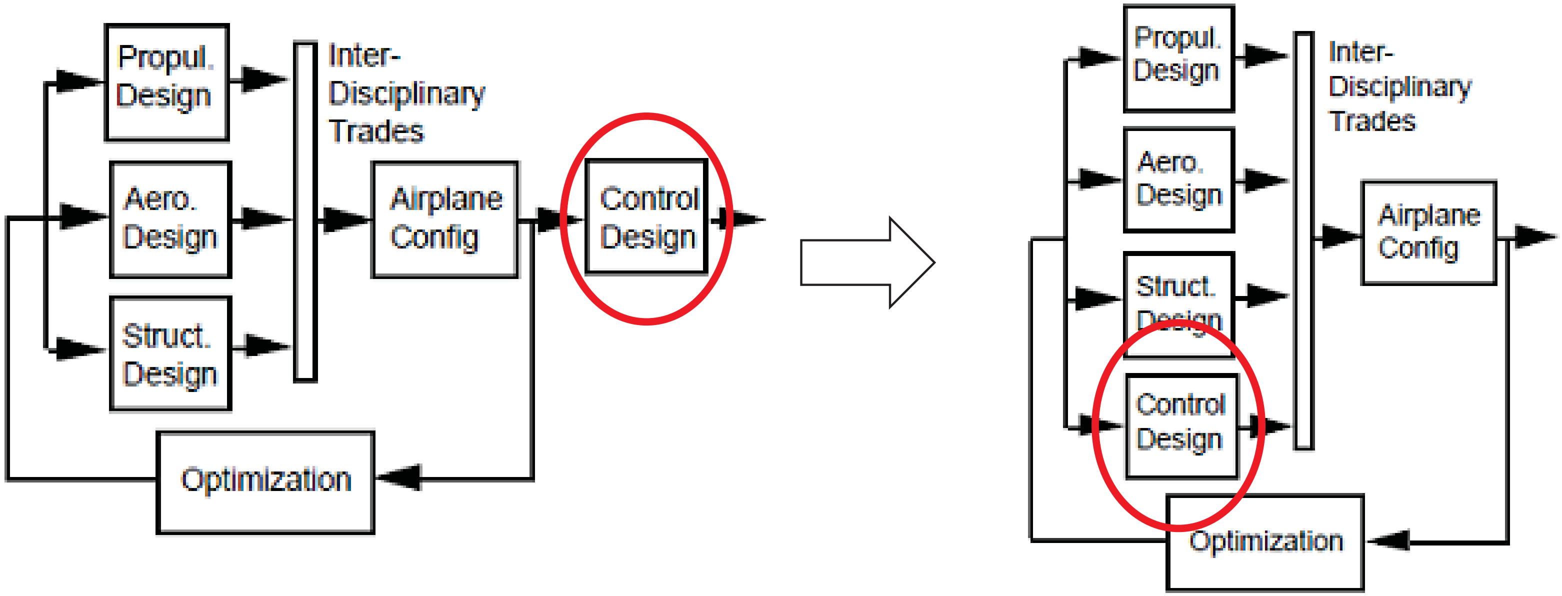
1st European Workshop on MDO for Industrial Applications in Aeronautics
24th-25th October 2017, Braunschweig

Thiemo Kier

DLR Oberpfaffenhofen
Institute of System Dynamics & Control

DLR

Flight Control System Design in the MDO loop



Anderson M.A. and Mason, W., „An MDO Approach to Control-Configured-Vehicle Design“,
6th AIAA/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, **1996**

Why is this important for the loads process?

CS 25.302 Interaction of systems and structures

For aeroplanes equipped with systems that affect structural performance,…

Appendix K of CS25 must be used to evaluate the structural performance of aeroplanes equipped with these systems.

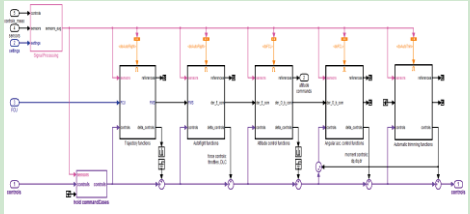
CS-25 Appendix K: Interaction of Systems and Structure

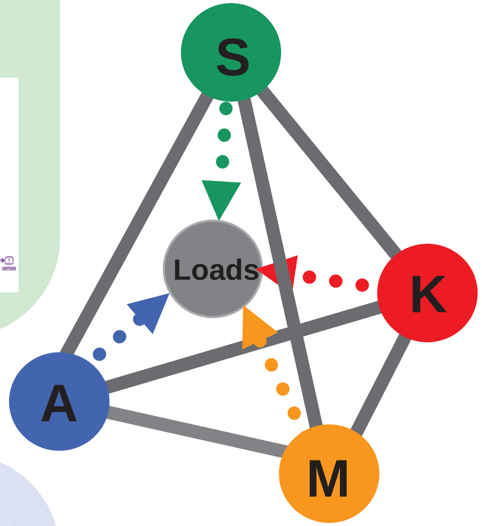
- **flight control systems,**
- **autopilots,**
- **stability augmentation systems,**
- **load alleviation systems,**
- **flutter control systems**, and
- fuel management systems.

Loads Analysis Model

Flight Control System

- Control Surface Allocation
- Manoeuvre and Gust Load Alleviation Functions
- Primary Flight Control Laws
- Sensors
- Actuators



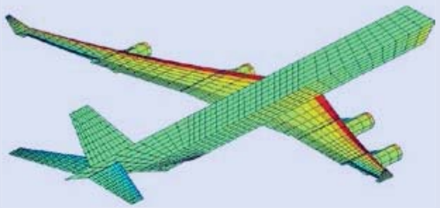


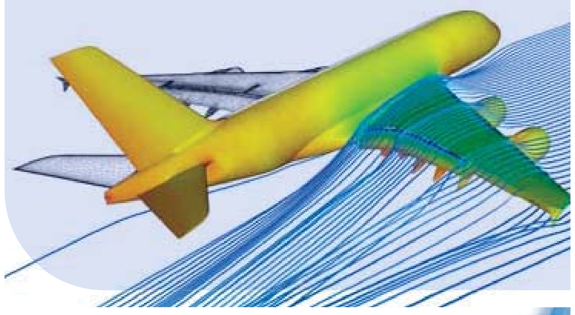
Stiffness

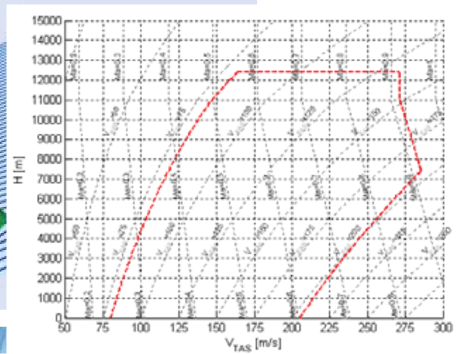
$$\begin{Bmatrix} u_a \\ u_o \end{Bmatrix} = \begin{bmatrix} I \\ -K_{oo}^{-1} K_{oa} \end{bmatrix} u_a = \begin{bmatrix} I \\ G_{oa} \end{bmatrix} u_a$$

$$K_{gg} = \begin{bmatrix} I & G_{oa}^T \end{bmatrix} \begin{bmatrix} K_{aa} & K_{ao} \\ K_{oa} & K_{oo} \end{bmatrix} \begin{bmatrix} I \\ G_{oa} \end{bmatrix}$$

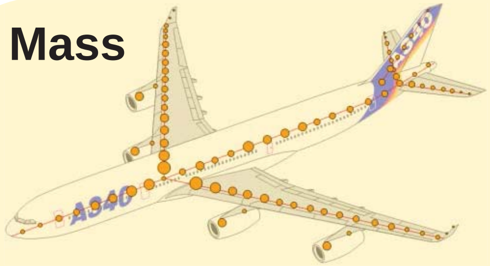
Aerodynamics

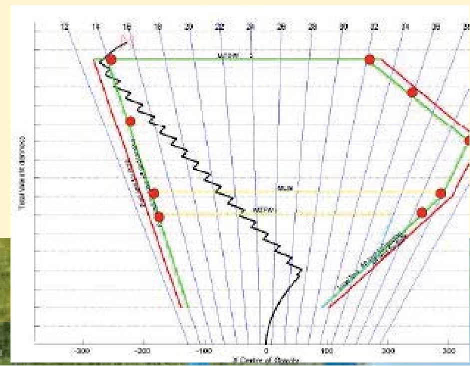


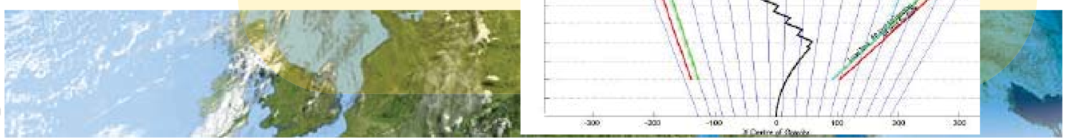


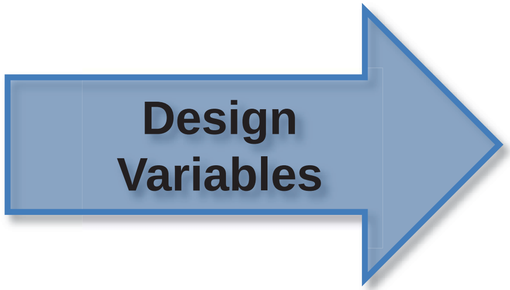


Mass

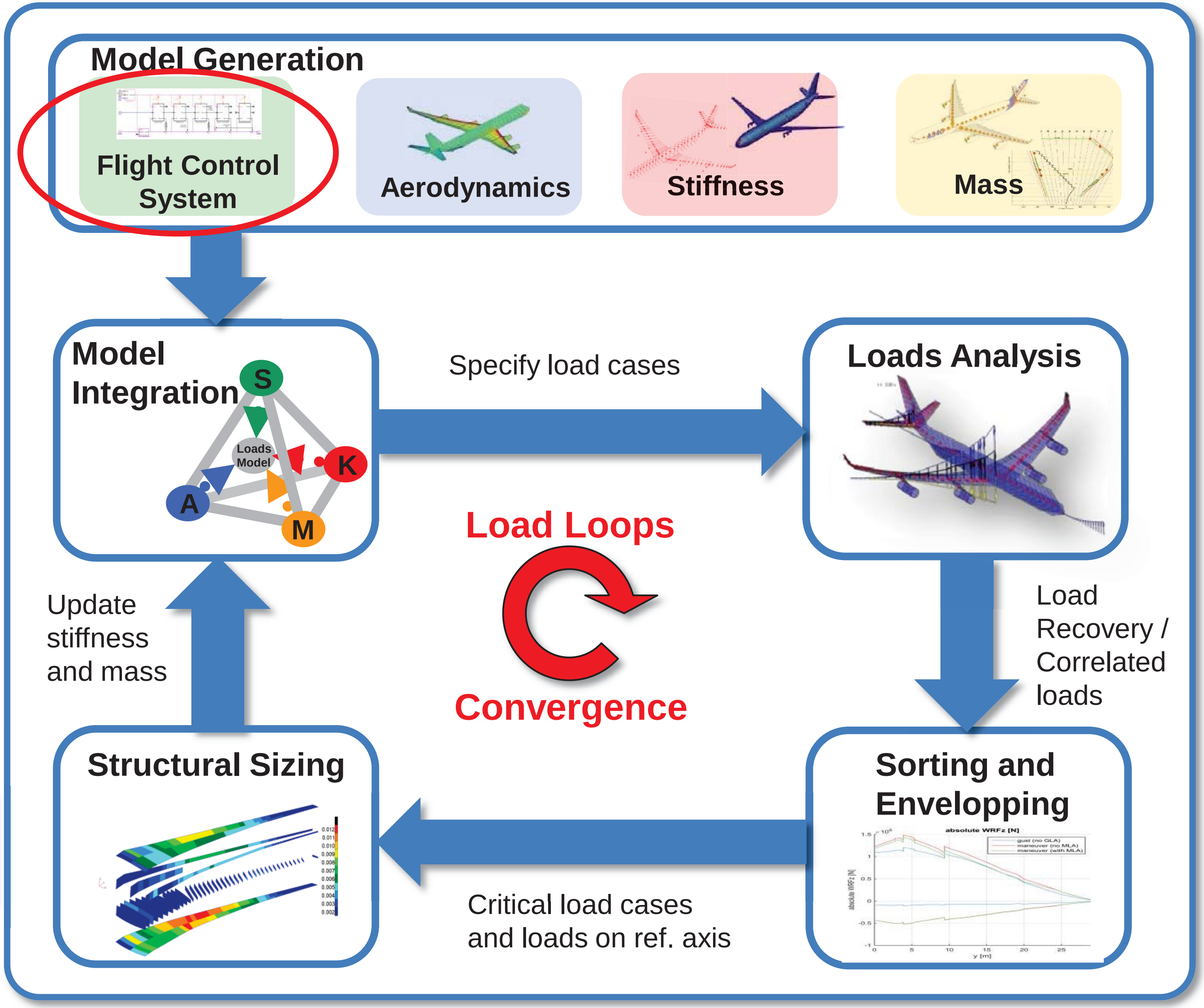


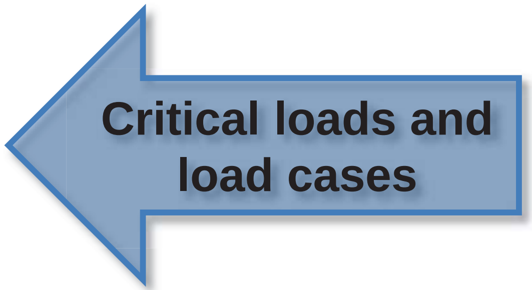






Loads Process



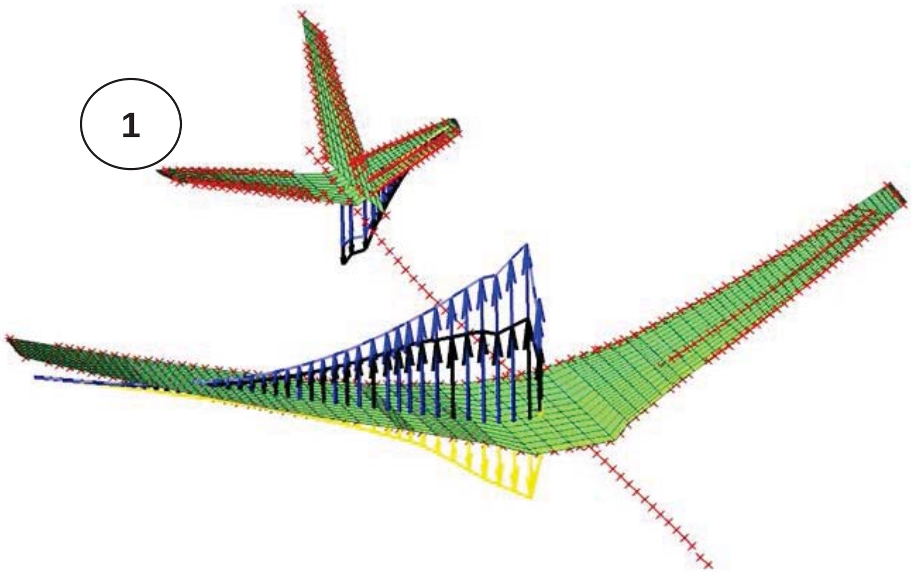


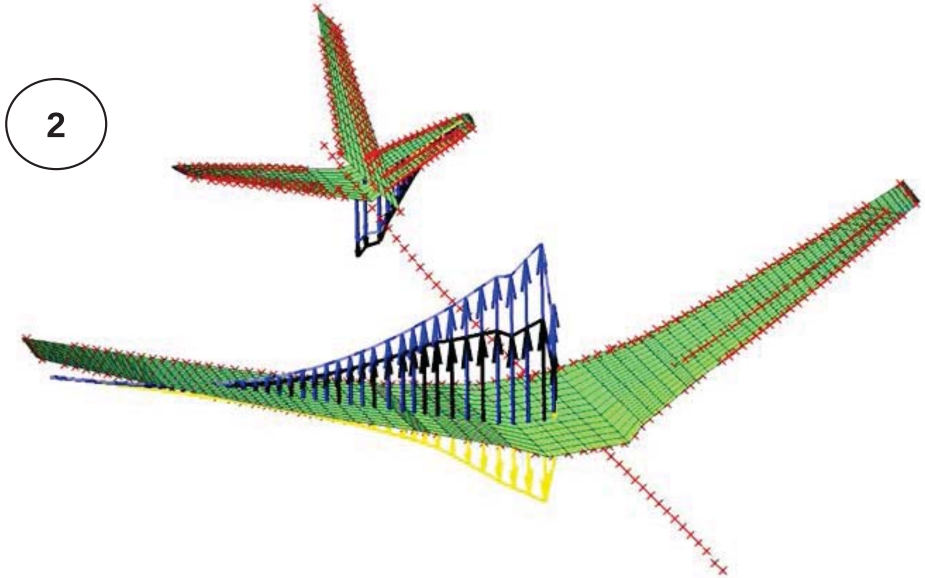
Control Surface Allocation: Roll Manoeuvre

- Using the outboard aileron for roll control at high dynamic pressures results in an reversal of the aileron.

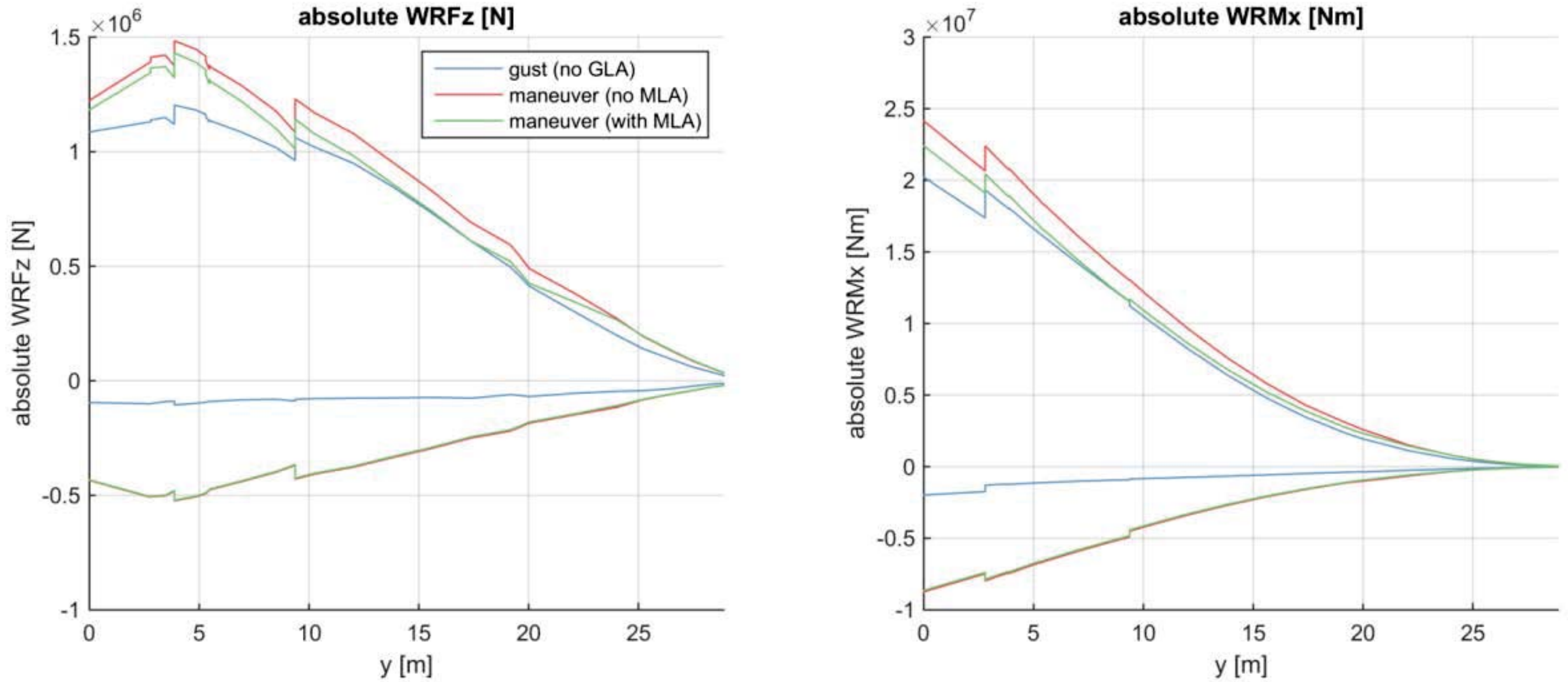
- Employing a structural c/s reversal constraint increases the mass

- Allocation/Scheduling wrt. Velocity, e.g. using roll spoilers and/or split or inboard ailerons at high dynamic pressures





Load Alleviation Functions



- When **no MLA** is considered, the **manoeuvre** cases will likely always be **critical**
- **With MLA**, manoeuvre and **gust** loads have the **same level**
- If the **wing loading is low**, gust loads will become critical and a **GLA is needed**

- Which C/S to use for LAF? Special C/S? Multifunctional C/S?
- Design of Flight Control System needs to be part of the MDO task.
  (Control Surface Placement, Allocation and Control Laws)

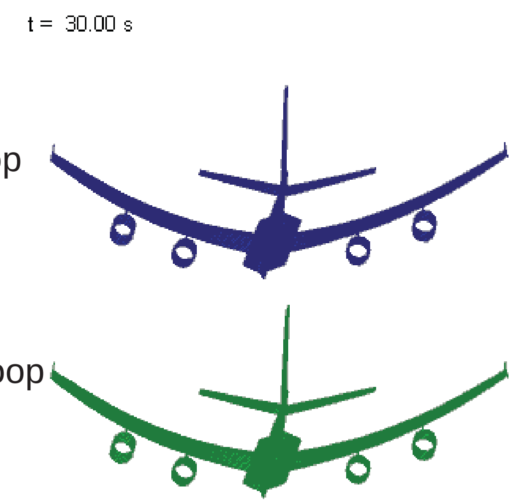
Time Domain Continuous Turbulence

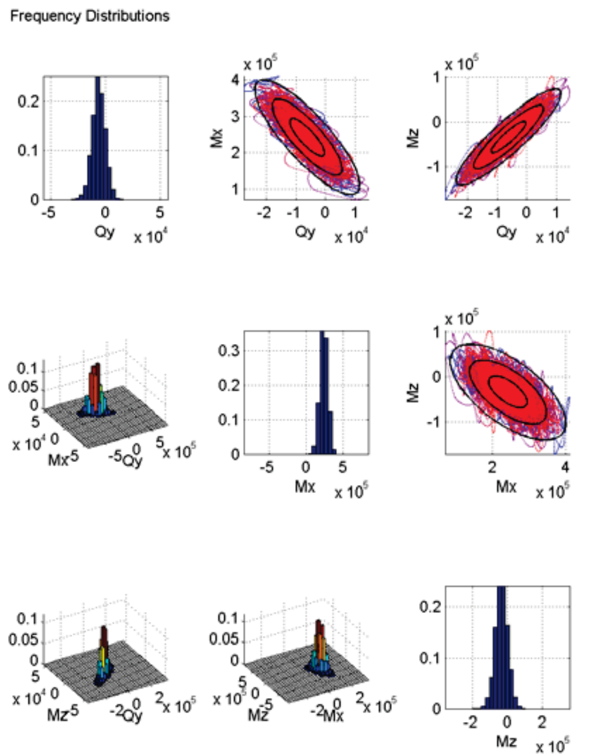
Lateral cont. turbulence (Dryden Spectrum)

- Simulation and Stochastic Analysis of Continuous Turbulence Load Cases
- Nonlinear Effects of Control Law on Structural Loads

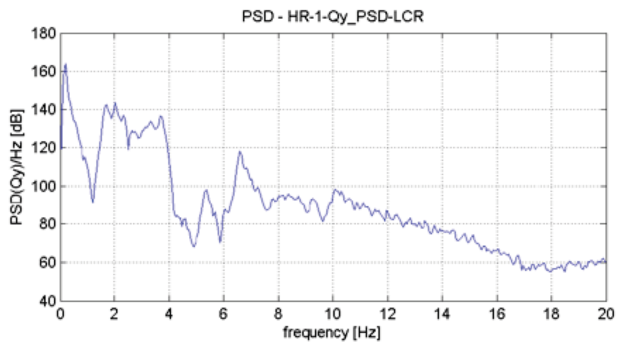
Open Loop

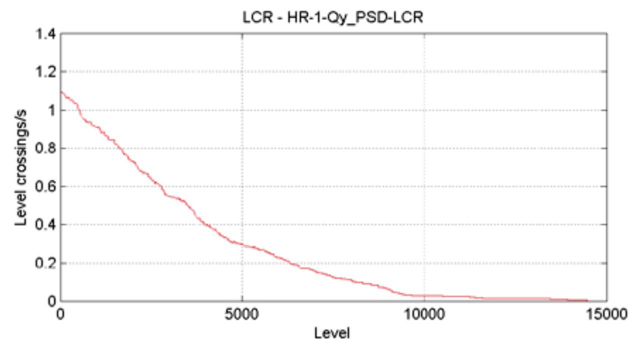
Closed Loop





Correlated Loads Distributions





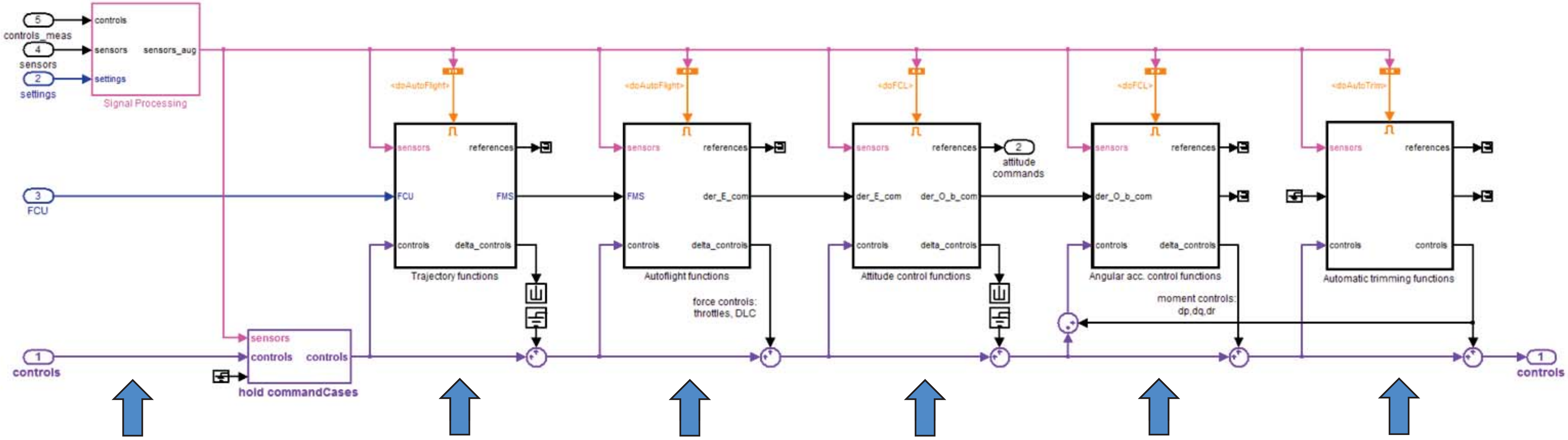
Power Spectral Density

Level Crossings

Accounting for Nonlinear Effects such as

- Saturation
- Rate limits
- Triggered activation

Fully Parameterized Prototype EFCS Generation



Signal Processing

Trajectory Following Functions (for Mission-simulations)

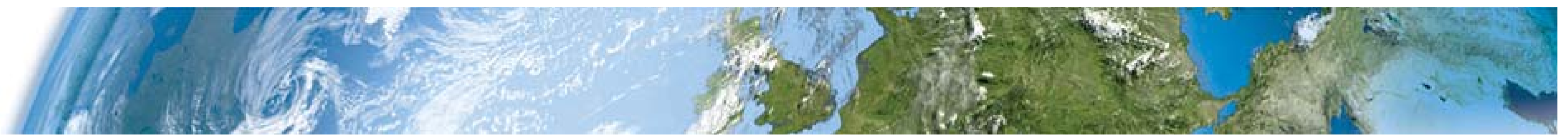
Autoflight Functions: (Auto-Throttle, DLC, etc.)

Attitude Control

Control of Angular Accelerations

Auto-Trim

- Model based, automated dynamic EFCS generation
- Based on HQ and architecture specifications
- Robust approach required
- Nonlinear Dynamic Inversion based EFCS prototype for MDO processes



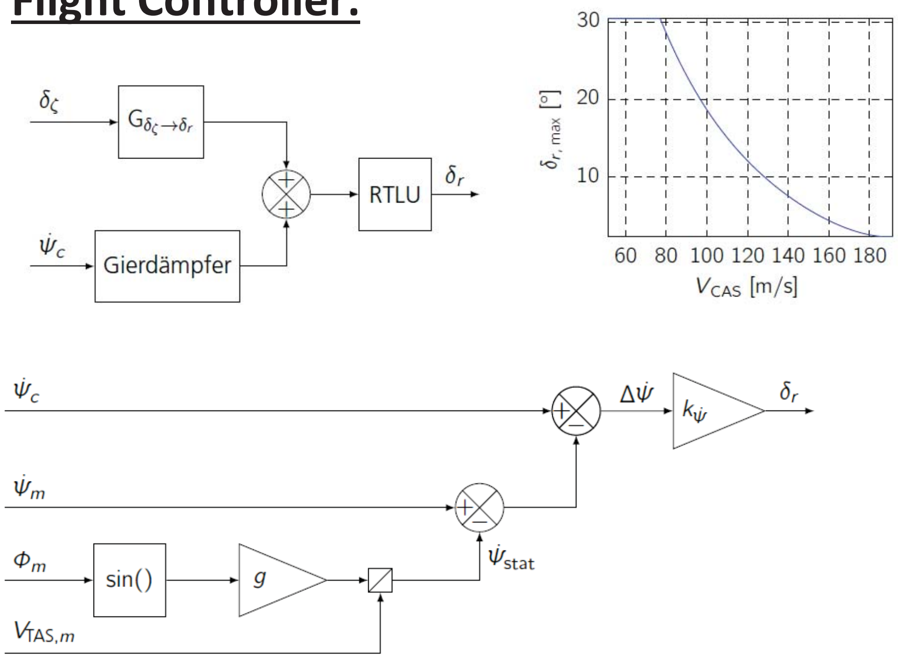
Yaw manoeuvre CS 25.351

- dependent on architecture of the controller (deflection limiter, yaw damper, control laws) and the flight mechanics (Dutch Roll) of the aircraft.
- Yaw manoeuvres are critical load cases for VTP sizing

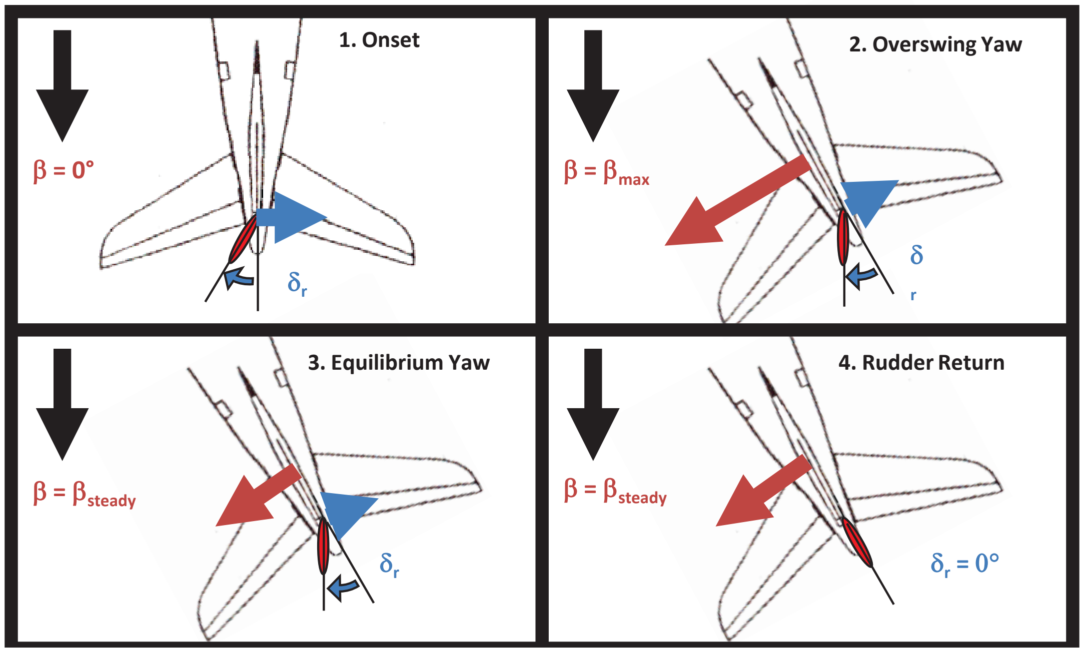
Mishap during an MDO run:

- Due to a wrong setting RTL was not active, resulting in a very heavy VTP
- and suddenly yaw manoeuvres appeared as critical cases for wing design

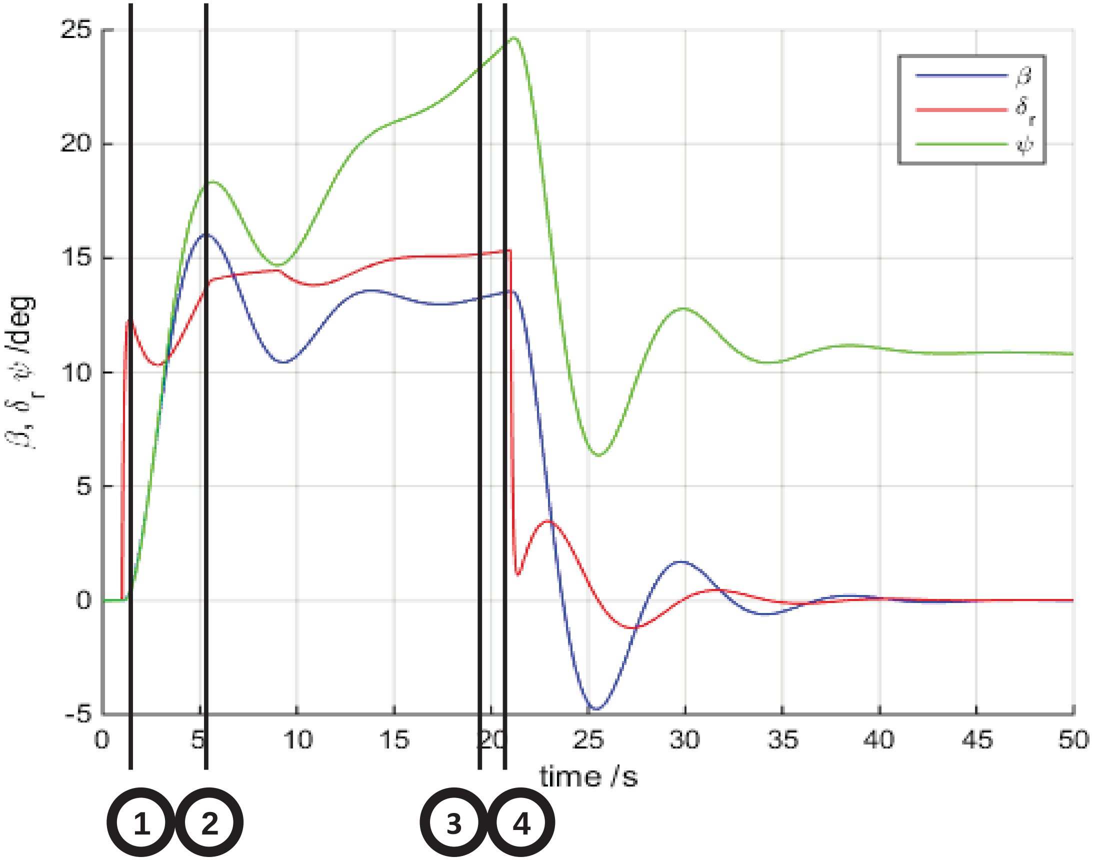
Flight Controller:

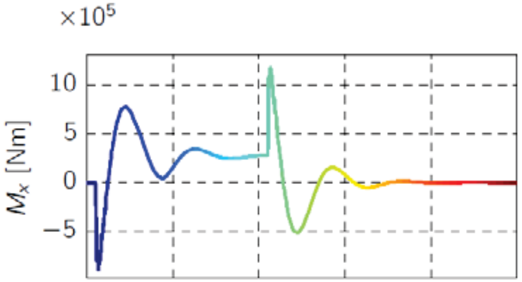


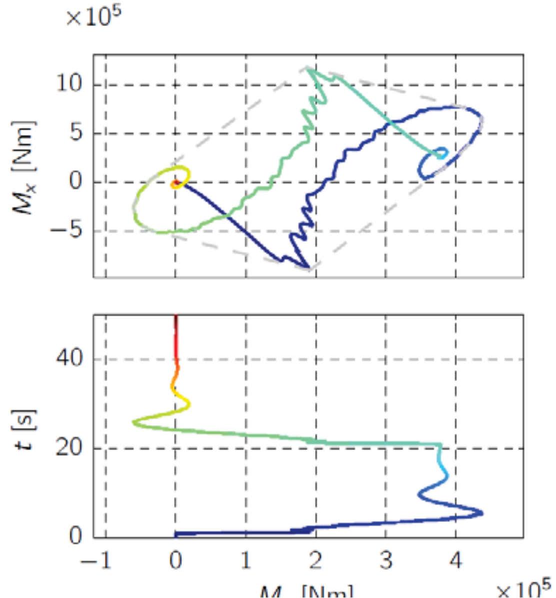
Phases of the yaw manoeuvre:



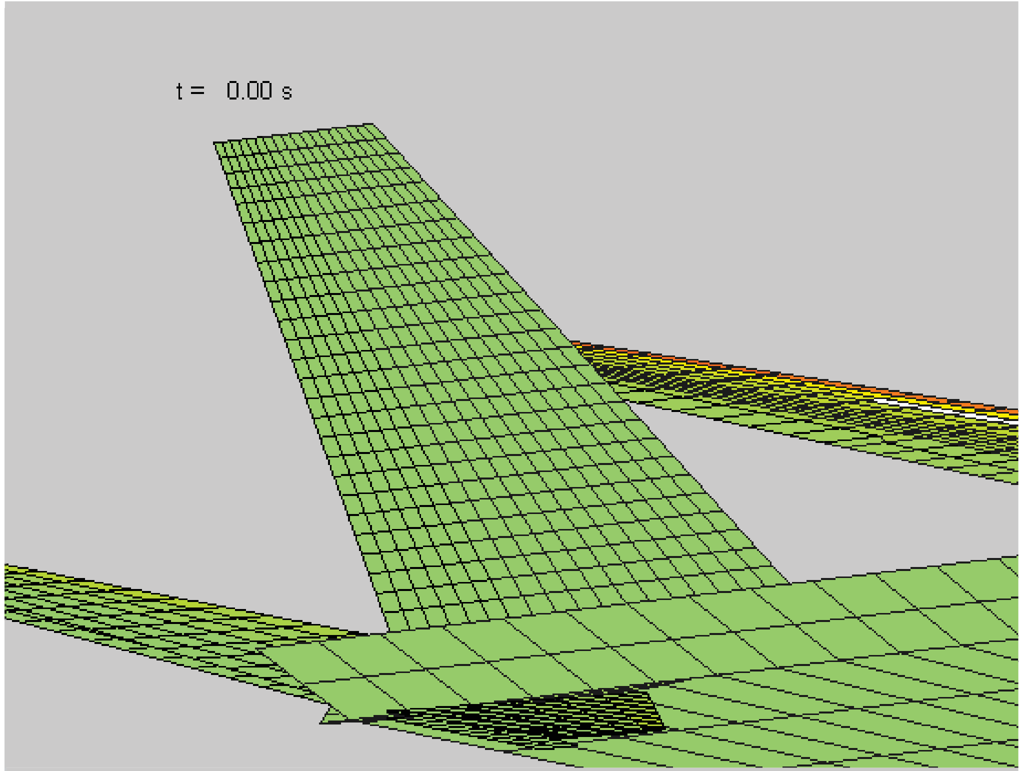
Dynamic Simulation of the Yaw Manoeuvre

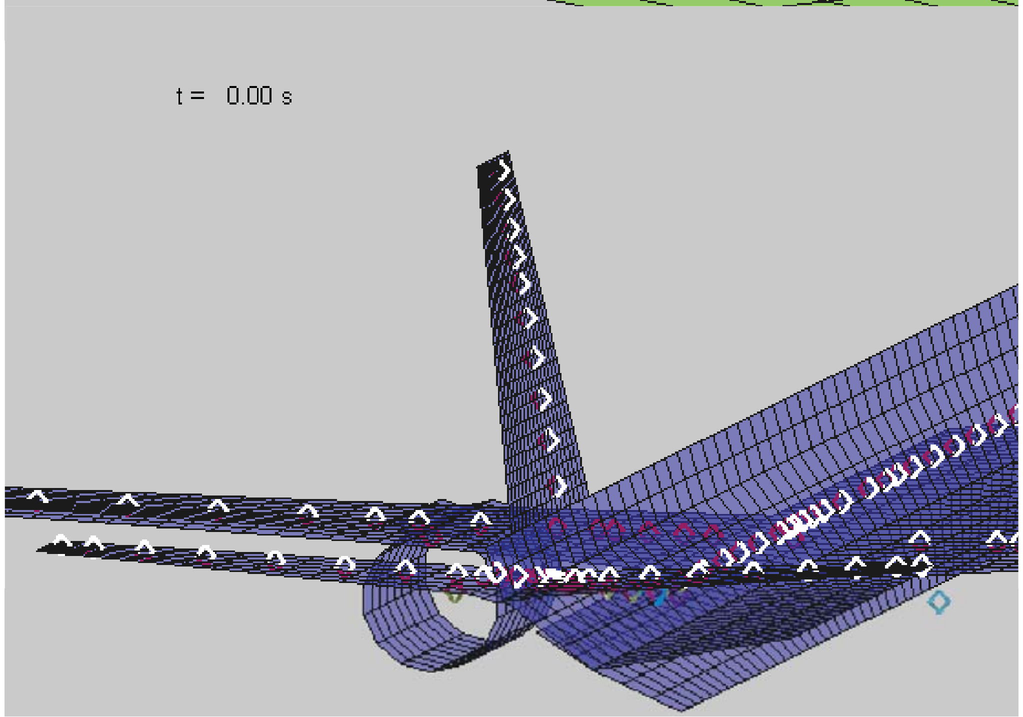




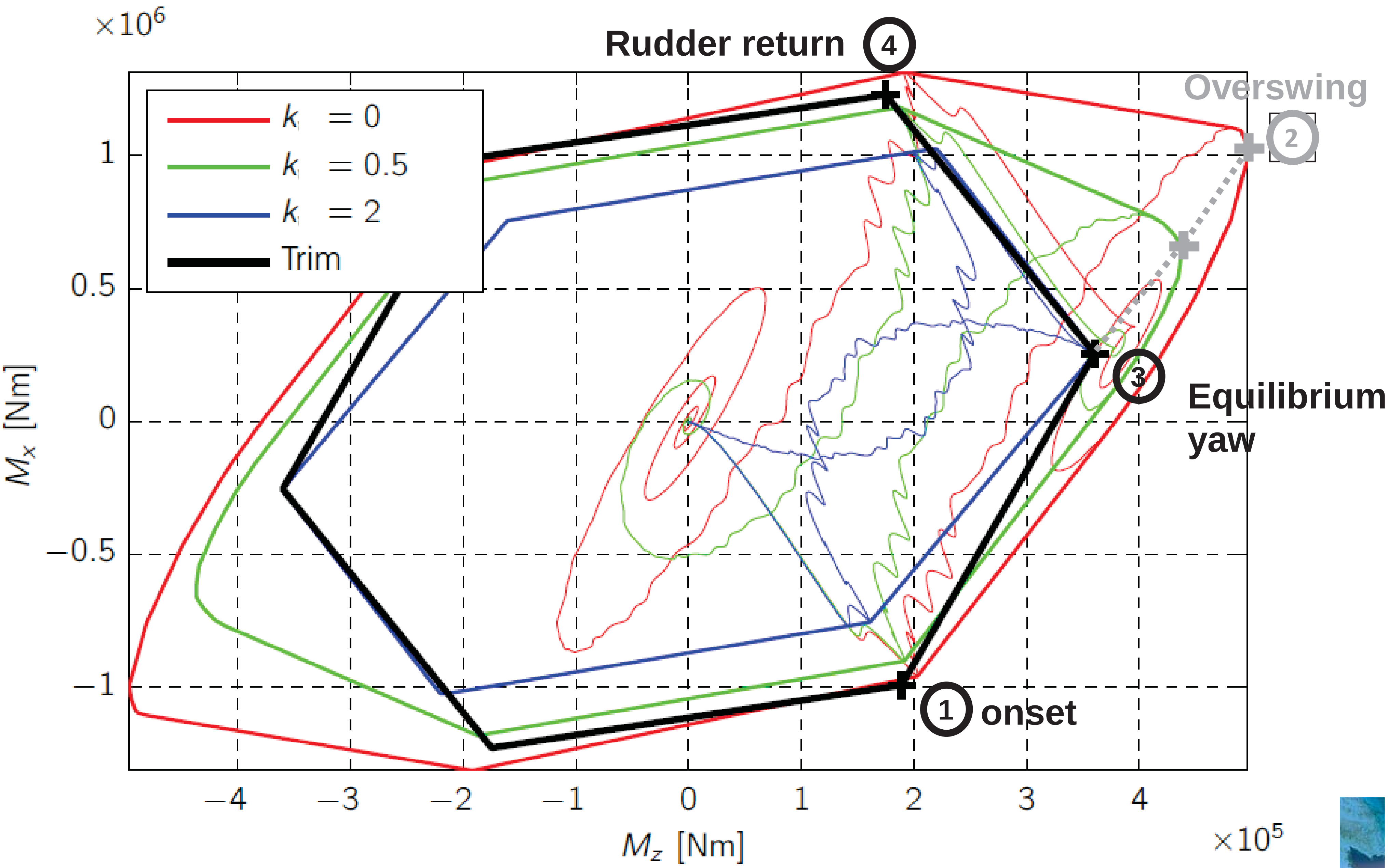


Bending and torsion moments at the VTP root





VTP Loads Comparison Dynamic Simulation and Trim



Aircraft Design Example – Interaction Flight Control and Flight Physics (Loads / HQ)

Example: **Increasing** the **span** to reduce induced drag

- Chord length at wing root is constrained due to landing gear integration
- Thus, the wing area increases

Loads Analysis – Load Alleviation Functions

- Wing Loading decreases
- Gust Loads become critical in the Loads Envelope
- Active Gust Load Alleviation required
- Side constraint: HTP Loads are increasing

Flight Dynamics – Primary Flight Control Laws

- Rolldamping C_{Lp} is increased
- Handling Quality constraint: Rolling bank to bank +30° to -30° Φ in 7 s

Optimization Parameters :

Control Surface -placement, -dimensioning, -allocation, -function assignment, -control

Thank you for your attention !
Questions ?

DLR