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AN EADS COMPANY

AIAC'2013

7th Ankara International Aerospace Conference

Past Activities and Recent Efforts in Multidisciplinary Analysis and Optimization for Conceptual and Preliminary Design at Cassidian

ANKARA INTERNATIONAL AEROSPACE CONFERENCE

September 11-13, 2013 @ METU, Ankara - TURKEY

Johannes Schweiger

Sept. 11-13, 2013

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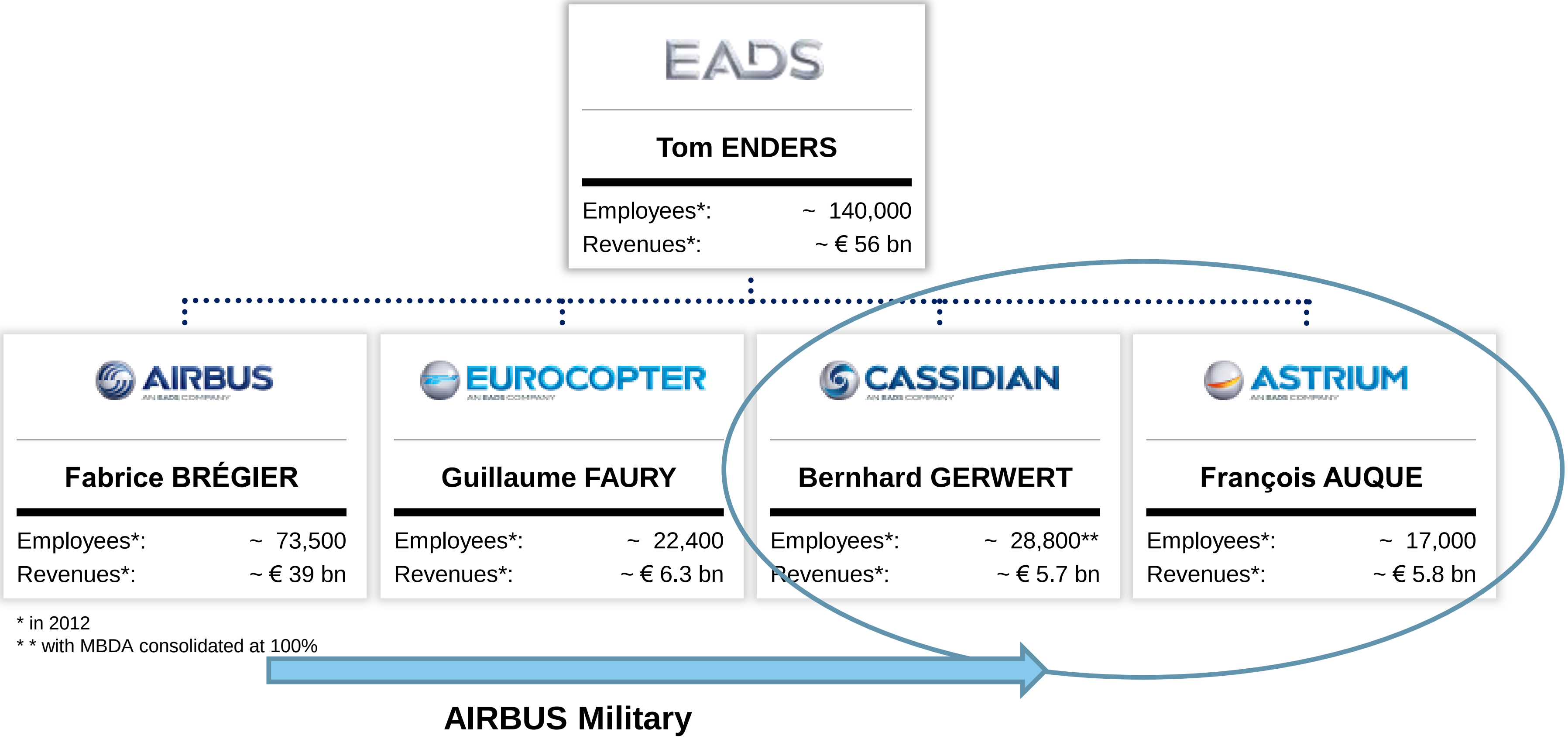
Multidisciplinary Analysis and Optimization for Aircraft Design at CASSIDIAN

Content

- CASSIDIAN and EADS: overview and heritage
- The term “optimization” in this context
- Needs for MDO from the aircraft side
- Early capabilities
- Past project applications
- Tools improvements
- Application for innovative design concepts
- Constraints and need for conceptual design tasks
- Some final remarks.

The Future EADS (Airbus) Group Organisation



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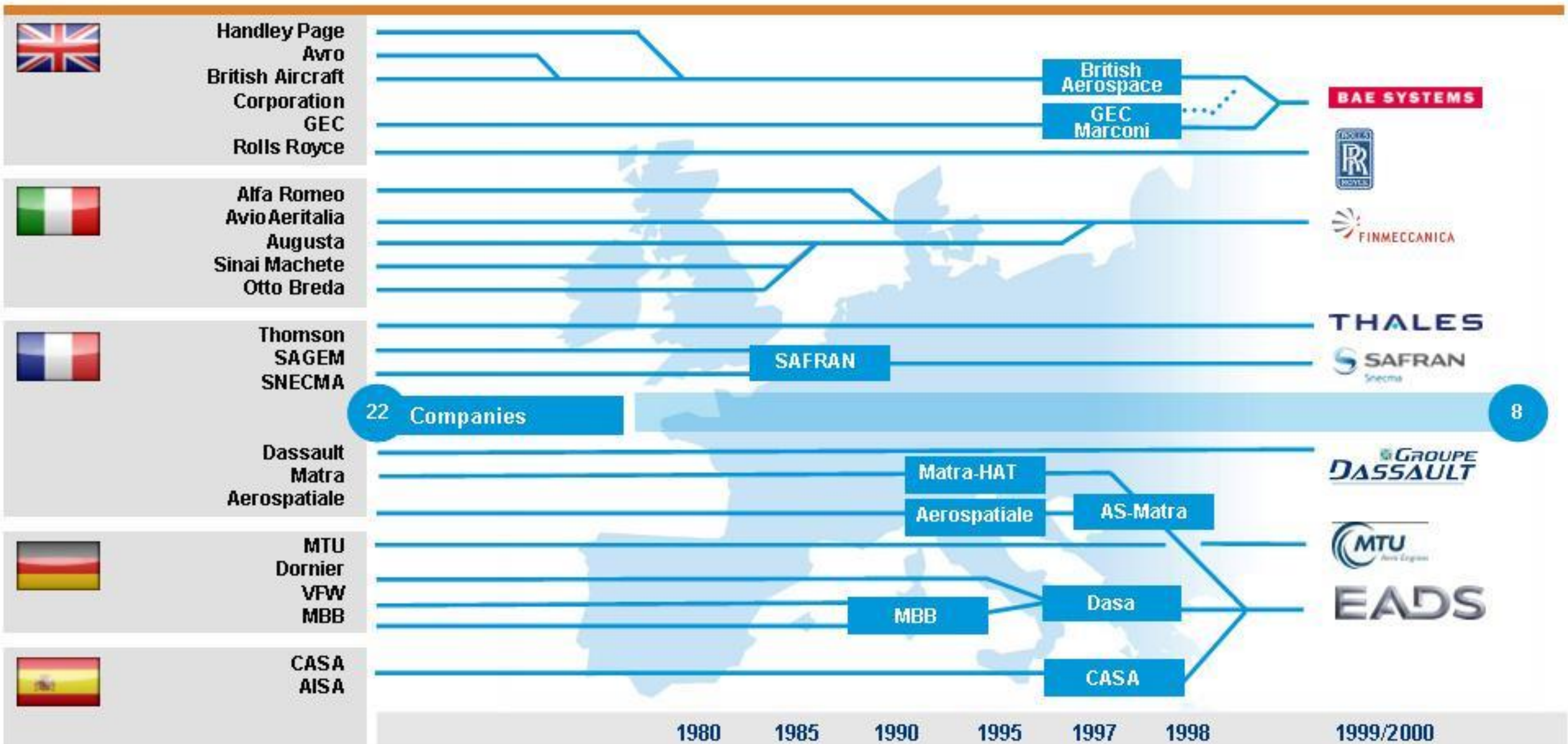
Consolidation in Europe



Some personal data

- Aerospace Engineering, Technical University of Munich, diploma thesis (at MBB): "Investigations on forward swept wings", including the "Design of a forward swept wing for the fighter aircraft TORNADO" (1980)
  - Aerodynamic characteristics
  - Conceptual design
  - Aeroelastic divergence and "Aeroelastic Tailoring" with Carbon Fibers
  - Structural optimization (with multidisciplinary constraints)
- Wing span extension study for the Airbus A-300 by means of a tailored wing tip (triggered by the oil shock)
- Solution for a coupled flight mechanic / structural dynamic instability on a flying wing project (for the Akaflieg Braunschweig glider SB-13
- Early project studies by means of formal MDO for the Eurofighter ancestors (TKF, ACA): wing, fin, and foreplane.
- Systematic research on "Aerodynamic design of fighter wings with aeroelastic considerations".
- Experimental aircraft X-31, trainer aircraft Ranger-2000
- Active and adaptive structures technology projects, EC project "3AS" (Active Aeroelastic Aircraft Structures).
- Technology Management (for structures and flight physics).
- Since 2011: Conceptual design with improved MDO capabilities.

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Additional Remark

NATO
RESEARCH AND TECHNOLOGY
ORGANIZATION (RTO)
THE APPLIED VEHICLE TECHNOLOGY
PANEL (AVT)

TECHNICAL COURSE

APPLICATION OF ADAPTIVE STRUCTURES
IN ACTIVE AEROELASTIC CONTROL

25-29 March 2002
METU-Ankara

COURSE DIRECTOR
Prof. Dr. Yavuz YAMAN

One part of my contributions was:
Structural Optimization and MDO in Industry

Question:
What has happened in MDO at CASSIDIAN since then?

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The Meaning of “Optimization” in this Context

Traditional:

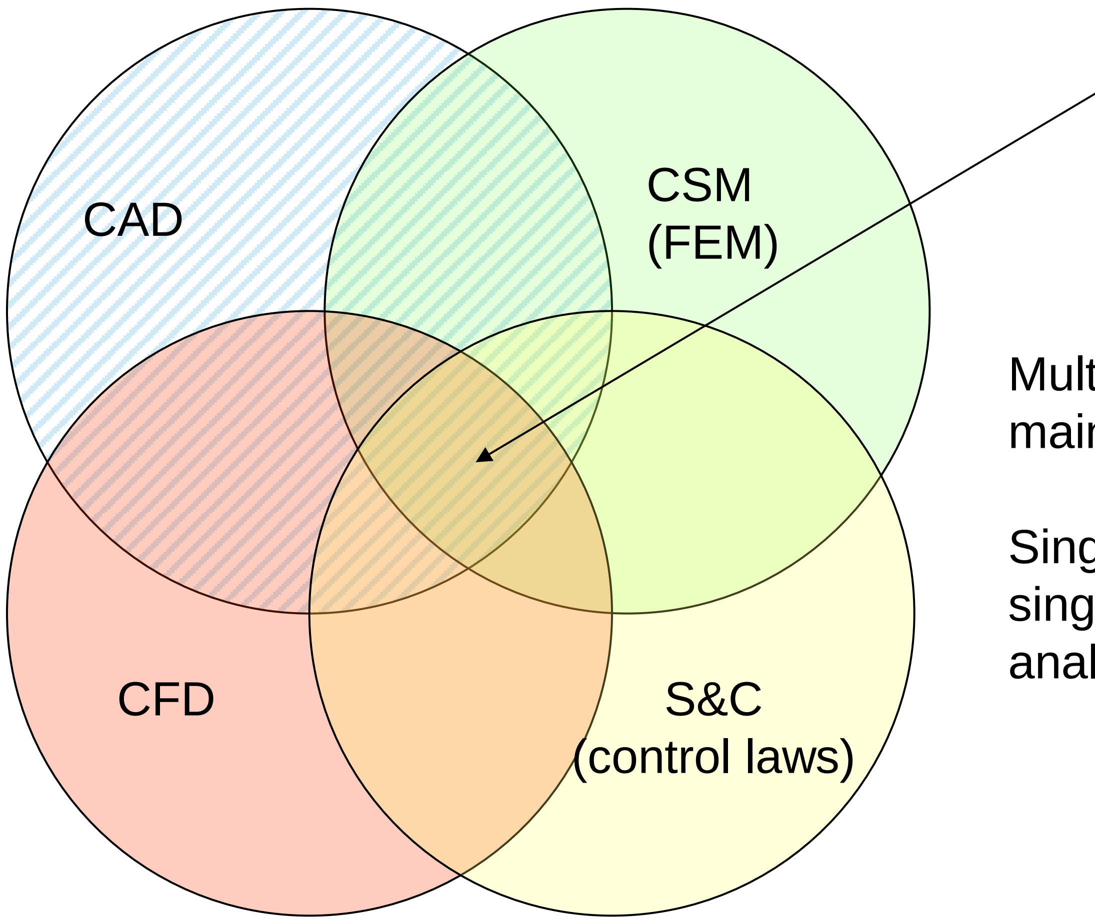
- Almost all engineering efforts are considered as “optimization” tasks.
- These activities typically happen towards the end of the development process (if the product is still “too heavy” or does not meet other requirements).
- Incremental improvements or refinements. “Repair solutions”.

Here:

- Formal mathematical processes to
  - Define a design objective (or “cost function”), usually the air vehicle’s mass,
  - Select a set of design variables that define the “objective function” (volume of structural elements, location of elements, topological arrangement),
  - Build and use appropriate analytical models that describe the problem (design requirements and constraints).
  - Make sure that the design will meet all requirements.
  - Identify the impacts from individual design requirements on the results (sensitivities)
  - Use efficient optimization strategies (ideally based on analytical gradients) **to find a good (“the best”) solution** that **meets all requirements (**within reasonable time).

Essential MDO Ingredients in Aircraft Design

Main areas of computational models



„Non-specific“:
- Mass properties
- Loads
- Aeroelasticity

Multiple-color areas:
main areas for MDO

Single-color areas:
single- disciplinary
analysis and optimization

+ efficient mathematical tools (sensitivities, minimization)!

"Multidisciplinary" (Analysis and Optimization)

Efforts in the context of this presentation are strongly focused on structures:

- Structural design models (the aerodynamic design is only analyzed)
- Structural design criteria (strength, buckling stability, stiffness)
- Aeroelastic constraints (flutter & divergence, control effectiveness)

Other disciplines

- Aerodynamic design
- Flight mechanics (Stability & Control)
- Actuation systems design

have their own optimization methods ("single disciplinary") and are here mainly represented by "translated" constraints in the structure oriented models, like:

- Deformation constraints (for flexible wing shapes)
- Static aeroelastic effectiveness constraints (for aerodynamic forces and moments, static stability, control effectiveness)
- Control surface hinge moments (for actuation system requirements).

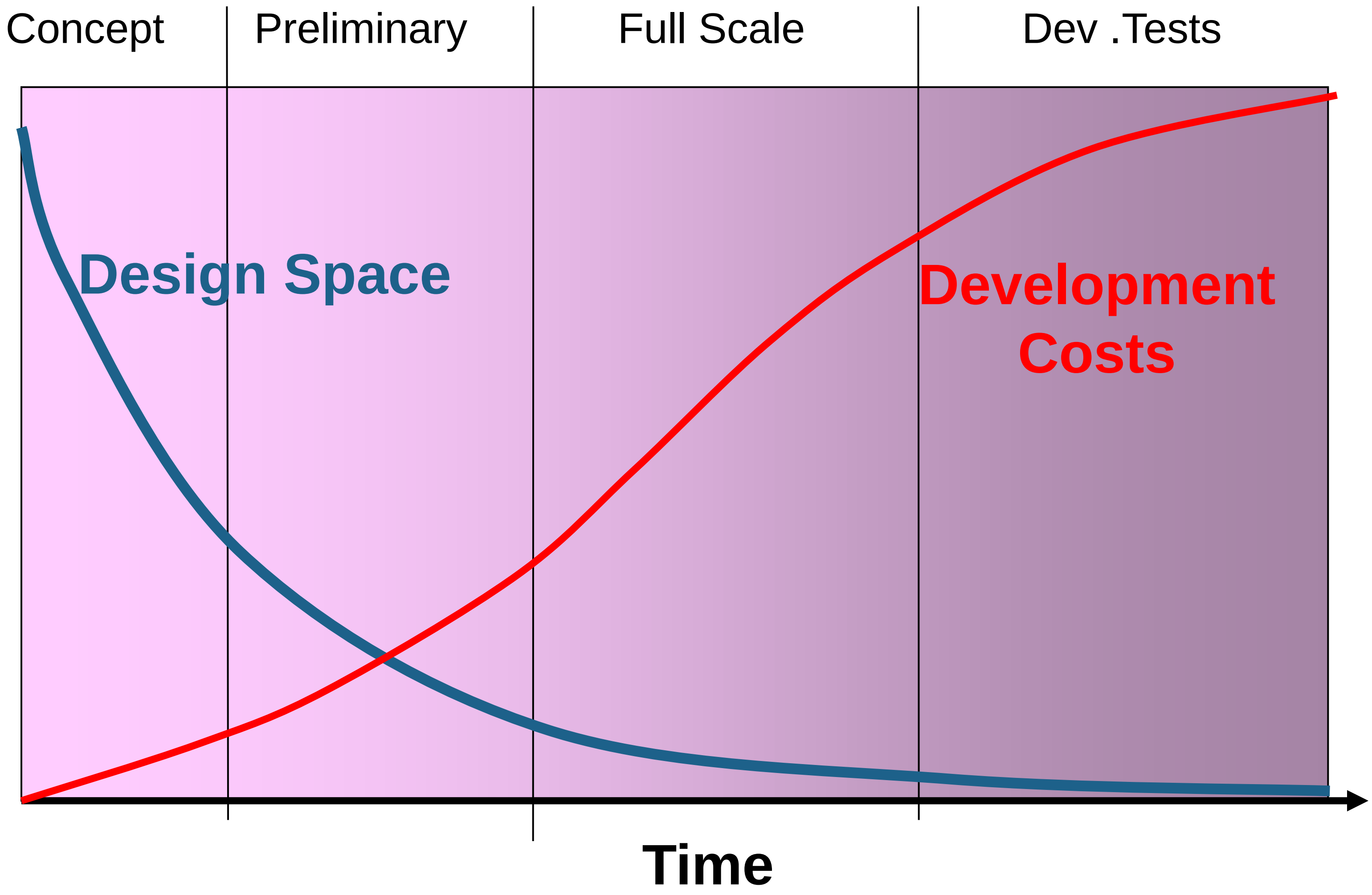
The Early Years of MDO (1980s)

Tools development and applications were triggered and enabled by:

- Higher performance for new fighters at high dynamic pressures (enabled by better engines) increase aeroelastic impacts like
  - Flutter stability (with various stores at wing stations)
  - Loss of roll control power
  - Yaw stability, rudder effectiveness
- New composite materials with highly anisotropic stiffness (and strength) characteristics create a much more
- New numerical analysis methods (FEM, CFD)
- Digital computers
- Increased awareness of interactions between the disciplines

Structural optimization (with aeroelastic constraints) was the starting point because aeroelastic needs for the design can not be expressed by simple (handbook) methods.

The Potential Benefits from MDO during the Aircraft Development Process



MDO Tools Situation in the Late 1970s

Formal structural optimization with (some) aeroelastic constraints:

- **FASTOP** (Flutter and Strength Optimization Program):
  - FEM models for (clamped) aerodynamic surfaces
  - Strength (for anisotropic materials only with fixed composition)
  - Flutter: only in a sequential approach (on top of strength)
  - No static aeroelasticity (for loads interactions, control effectiveness).
  - Fully strength design (type: optimality criteria)
- **TSO** (Aeroelastic Tailoring and Structural Optimization)
  - Continuum plate model
  - Optimizer: sequential unconstrained minimization technique (SUMT)
  - Various aeroelastic constraints
  - Fiber angles as design variables (in addition to polynomial coefficients for the plate thickness distributions)
  - Aerodynamic analysis (drag polar) for the deformed shape.

Example: Forward Swept Wing

Questions:

- What are the advantages/disadvantages compared with other wings?
  - Aerodynamic (high speed, low speed)
  - Stability and control, stall characteristics
  - Design loads
  - “Inboard” architecture (payload volume and location
- What is the aeroelastic divergence speed of a certain design?
- What are the impacts (sensitivities) from the wing‘s geometry?

- How can the divergence speed be increased most effectively by structural reinforcements?
- How should the composite material be composed (fiber orientations, layer thicknesses)?

Fig. 1 FORWARD SWEPT WING STUDY AIRCRAFT

Forward Swept Wing

Analytical structural design tasks:

- What kind of composite (fiber angles, global and local composition)?
- Material properties and design allowables?
- Aeroelastic divergence (and flutter) analysis
- Design loads?

Available tools and data:

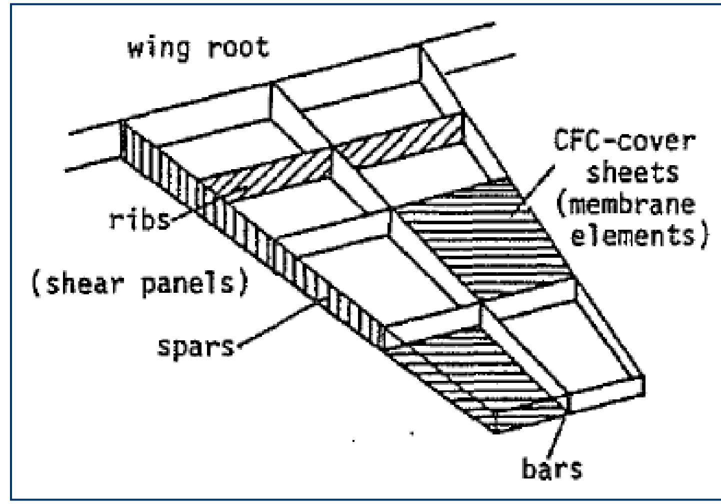
- FASTOP (Flutter and Strength Optimization Program)
- Material data base only for symmetric 0/+45/-45/90 degree laminates
- Loads via FASTOP-internal vortex lattice method (for rigid condition only).

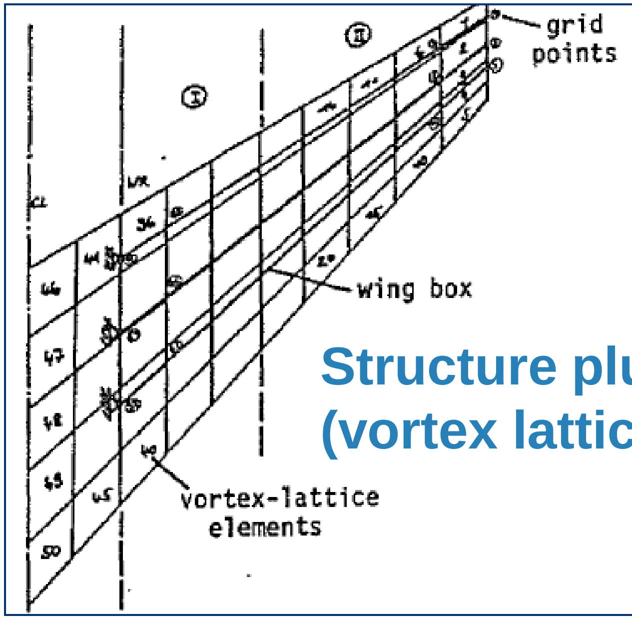
Restrictions and limitations:

- How to orient the fibers and distribute the material for higher divergence speeds?

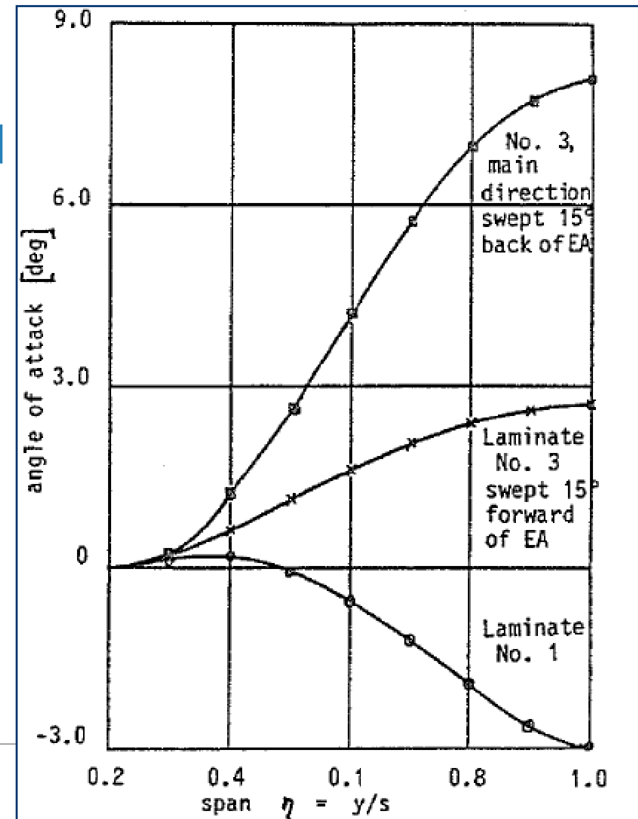
Forward Swept Wing

Structural model architecture





Structure plus aerodynamic model (vortex lattice, doublet lattice)

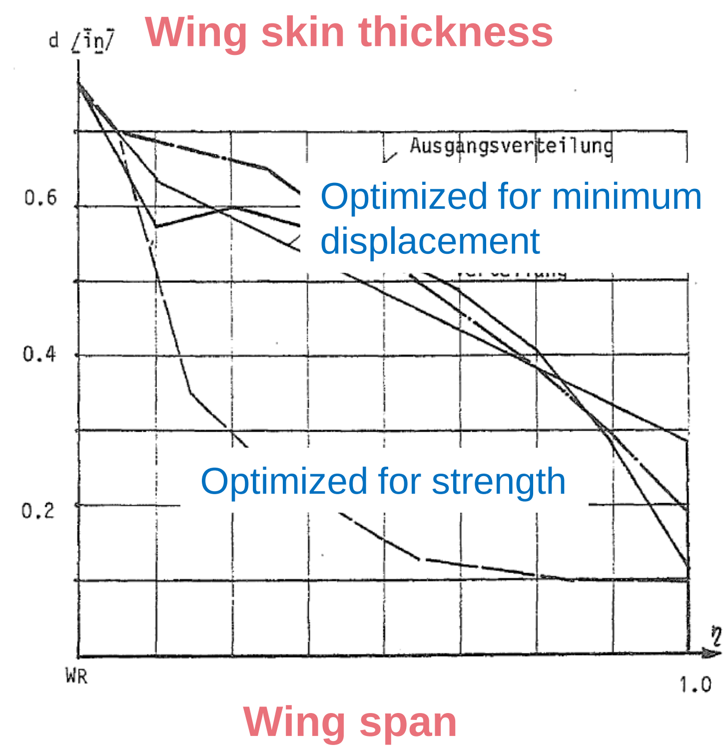


Deformation (twist along span) for three different laminates (fiber orientations, global volume)

Forward Swept Wing:

Required steps to perform the "optimization" in 1980

- Find fiber orientations for high divergence speeds by a beam model (with constant thickness and no considerations for strength).
- Apply the "best" composites (with estimated thickness composition) to the FASTOP FEM model and do structural optimization (with constant composite composition).
- Try to find the best thickness distribution along span with constant material volume for minimum tip displacement (high divergence speed) by another program.
- Combine the solutions.



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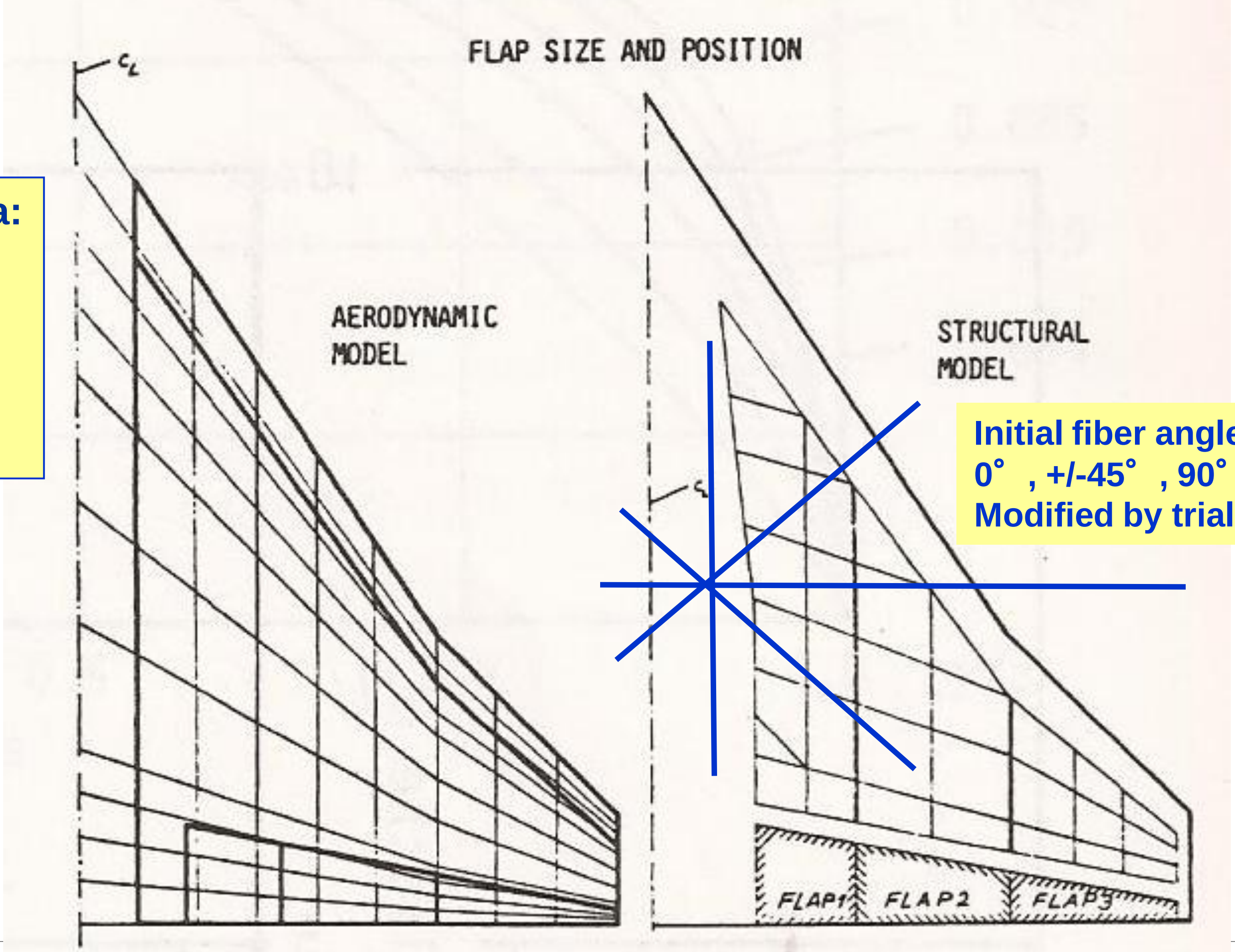
Analytical model for early Eurofighter („TKF“) wing structure and control surface geometry

Design criteria:
- Strength
- (Buckling)
- Flutter
- Aileron (roll) effectiveness



Initial fiber angles:
0°, +/-45°, 90°;
Modified by trial and error

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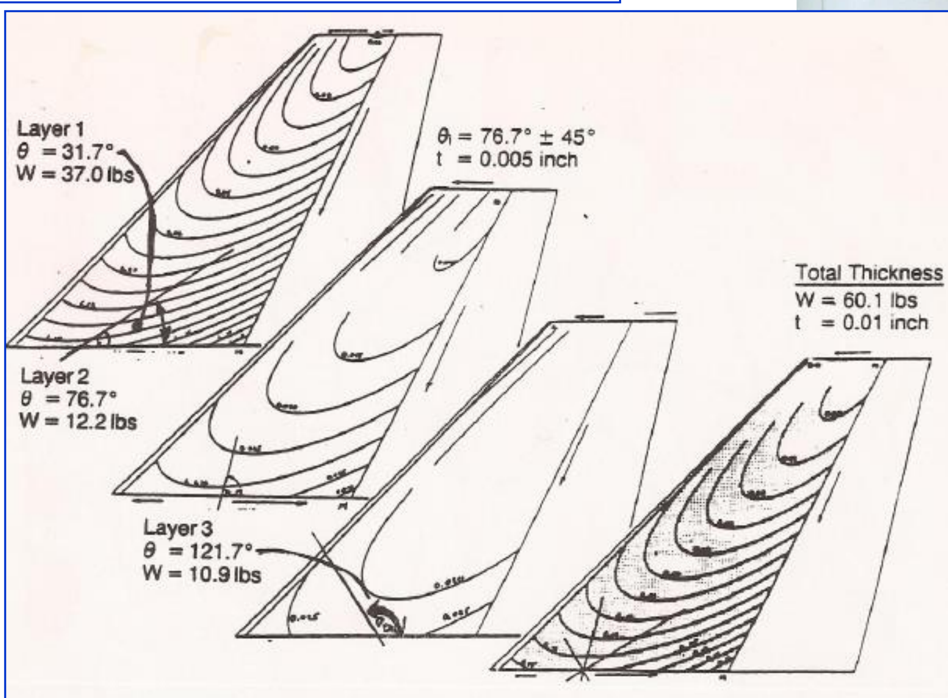
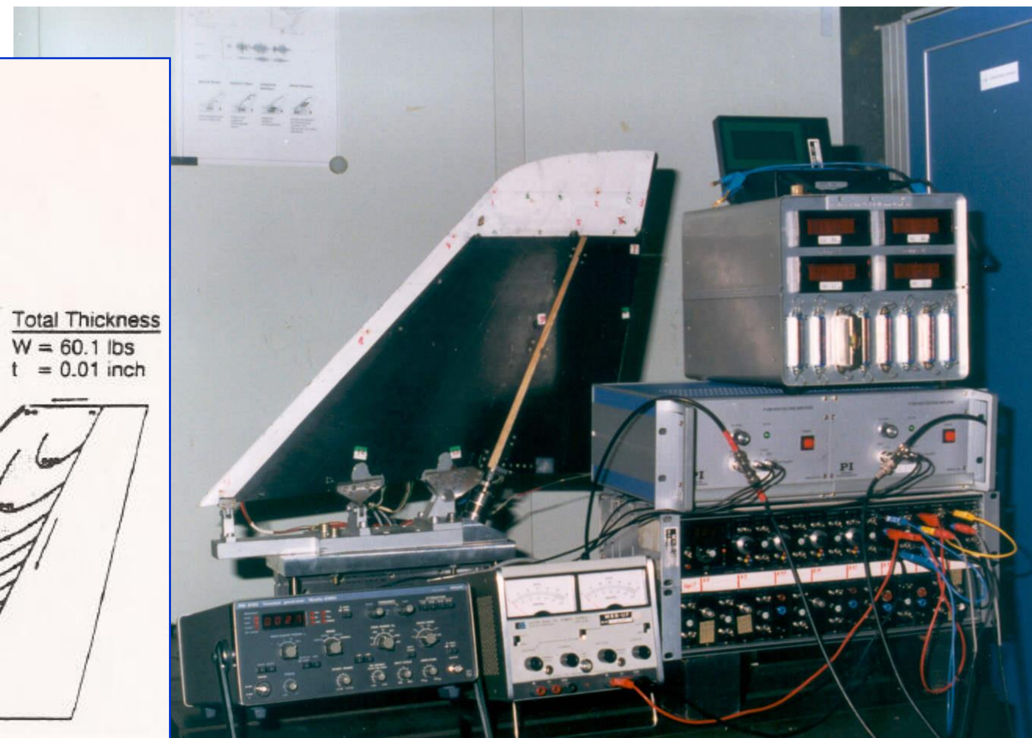
1982: New capabilities by TSO: “exotic” composites with optimized fiber orientations

- Quality of results and manufacturing feasibility verified by a transonic aeroelastic wind tunnel model (“ACA Fin”)
- Replica model design from full scale results

Skin thickness contours



Transonic aeroelastic wind tunnel model



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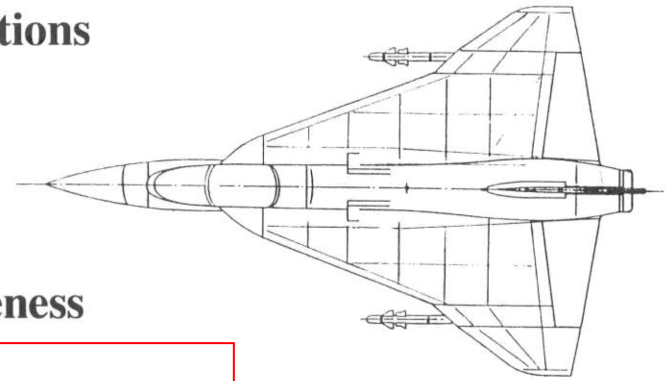
Demonstration of new design capabilities for a light combat aircraft project

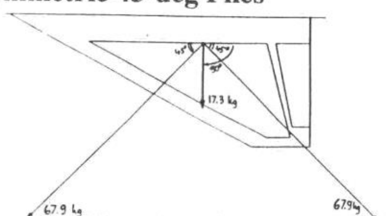
Light Weight Fighter Wing Design

Wing Skin Thickness and Fiber Orientations Optimized for
- **Strength,**
- **Flutter, and**
- **Aileron Rolling Moment Effectiveness**



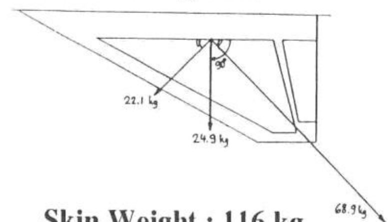
Light Weight Fighter Wing
Optimization Results with Different Design Spaces

Fixed Orientation, Symmetric 45-deg Plies



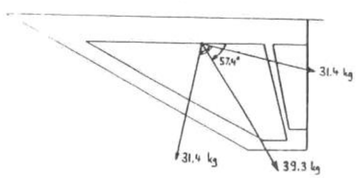
Skin Weight : 153 kg

Fixed Orientation, Unbalanced 45-deg Plies



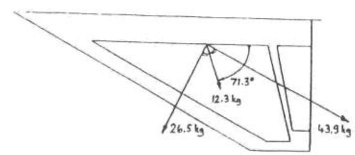
Skin Weight : 116 kg

All Plies are Free Rotate Together, Symmetric 45-deg Plies



Skin Weight : 102 kg

All Plies are Free to Rotate Together, Unbalanced 45-deg Plies



Skin Weight : 83 kg

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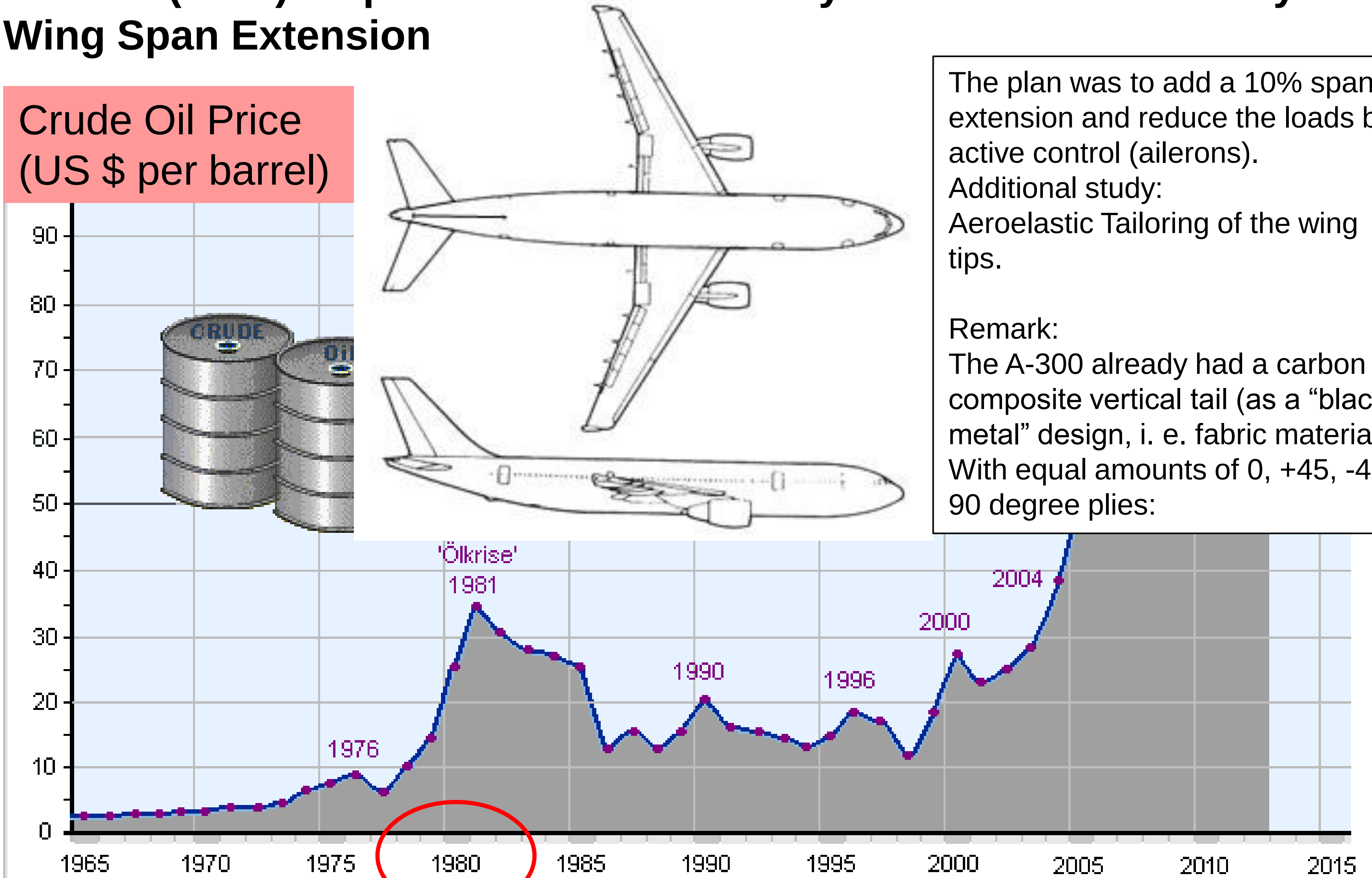
An early "Aeroelastic Tailoring" attempt for a commercial transport aircraft (1981): Improve the fuel efficiency of the Airbus A-300 by a Wing Span Extension



The plan was to add a 10% span extension and reduce the loads by active control (ailerons).
Additional study:
Aeroelastic Tailoring of the wing tips.

Remark:
The A-300 already had a carbon composite vertical tail (as a "black metal" design, i. e. fabric material With equal amounts of 0, +45, -45, 90 degree plies:

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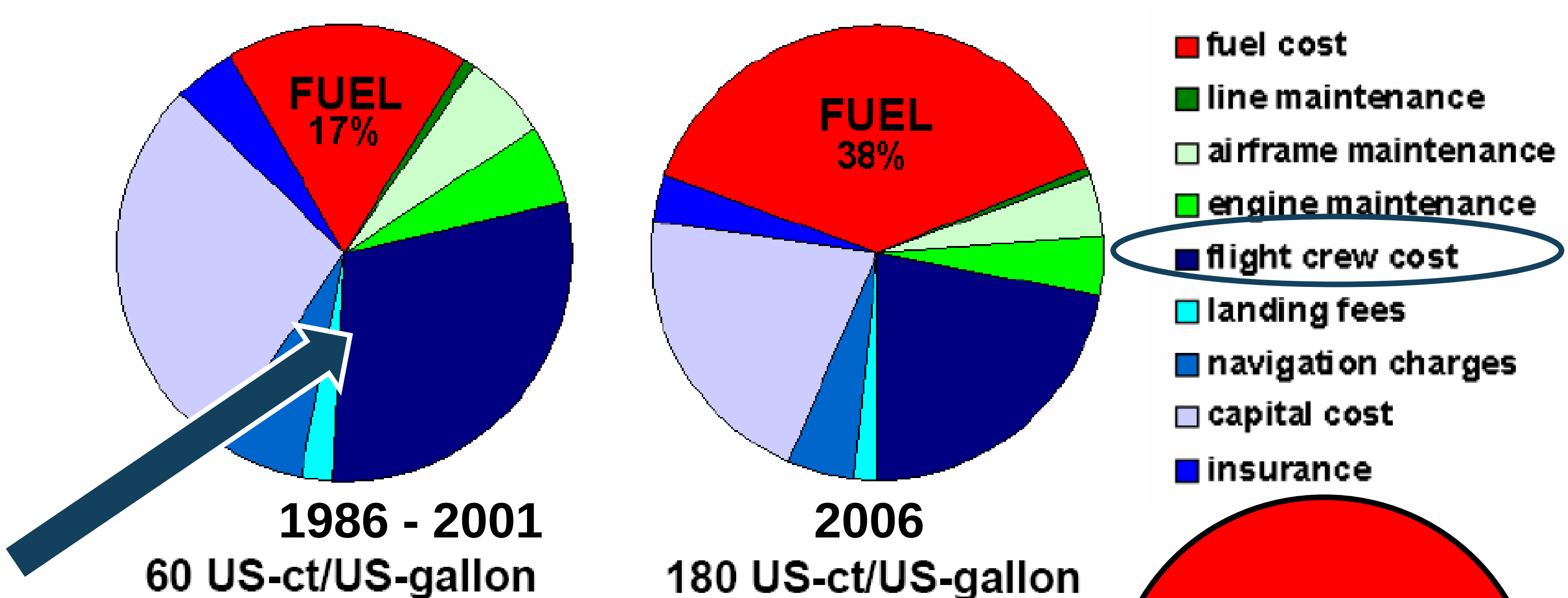
The role of external factors for multidisciplinary optimization efforts: fuel price, flight crew cost

Chart from the KATnet presentation at the 2006 EC Aeronautic Days:



The flight crew cost had already been reduced by a 2 instead of 3 cockpit crew prior to this time (first for Airbus)

Fuel in 2008: 100 % of the total 2006 DOC!

July 2008: 430 US-ct/US-gallon
Today (Sept. 8th 2013): 310 US-ct/US-gallon

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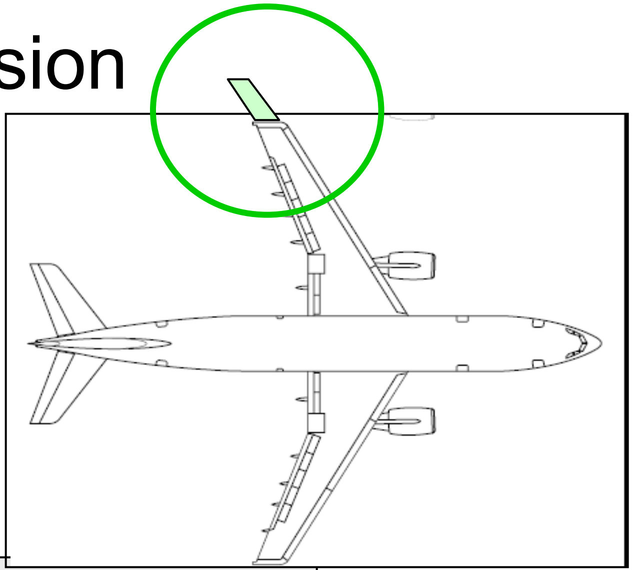
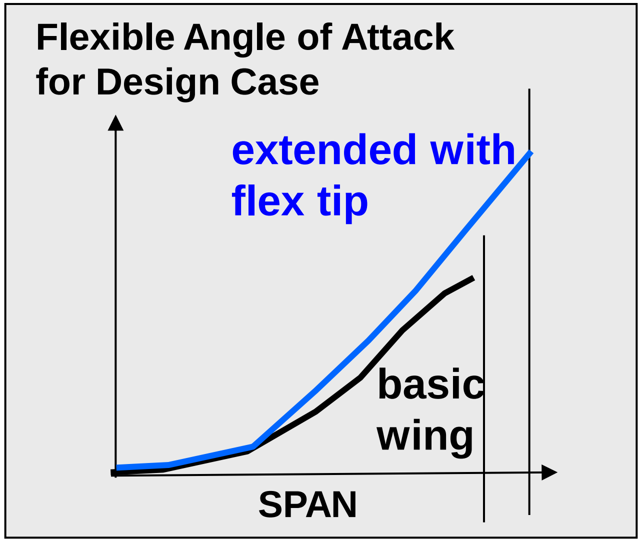
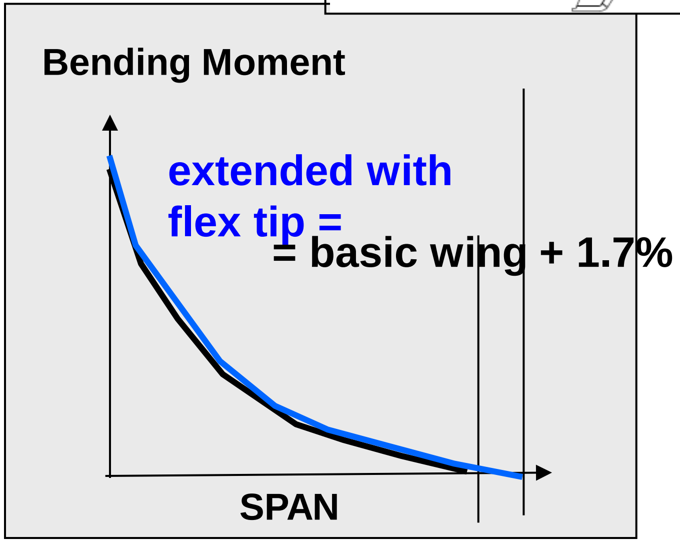
1981: Aeroelastic Tailoring study for Airbus A-300 with wing span extension

Passive solution:
“Tailored tip” with high bending flexibility



•Rigid bending moment increase: 10%
•with flex tip: 2%





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New capabilities at MBB with TSO (Aeroelastic Tailoring and Structural Optimization)

- Fiber orientation and individual layer thickness as design variables
- Trimmed aeroelastic load case
- Impacts from elastic deformations on the aerodynamic drag.

New features added at EADS:

- New optimization strategies (to start with infeasible designs)
- Supersonic unsteady aerodynamics
- Calculation of hinge moments
- FEM model generator for TSO plate model results. (This was applied to the Eurofighter wing skin optimization results in 1986.)

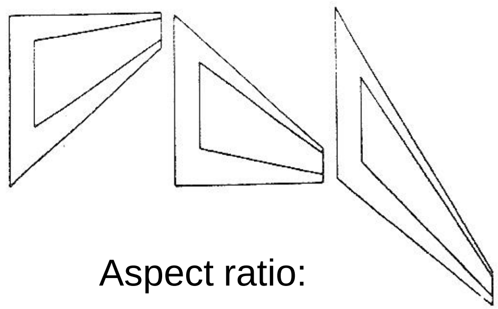
Integration of aeroelastic considerations into the aerodynamic design process of fighter aircraft wings

German MoD R&T project (1984 – 1986, together with Rockwell International)

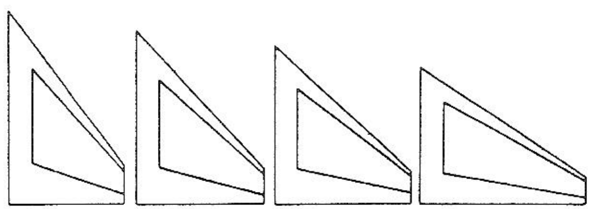
- Investigation of sensitivities of the main external wing geometry parameter (sweep angle, aspect ratio, taper ratio, thickness ratio) on the structural design with and without static and dynamic aeroelastic constraints.
- Flexibility impacts on drag and maximum lift
- Wing control surface shape, required hinge moments, and actuator force and stiffness sensitivities
- MDO tools improvements.

Aeroelastic tailoring study: Wing geometry and aeroelastic sensitivities

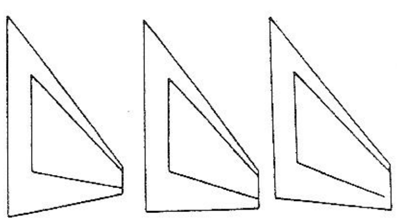
Sweep angle:



Aspect ratio:

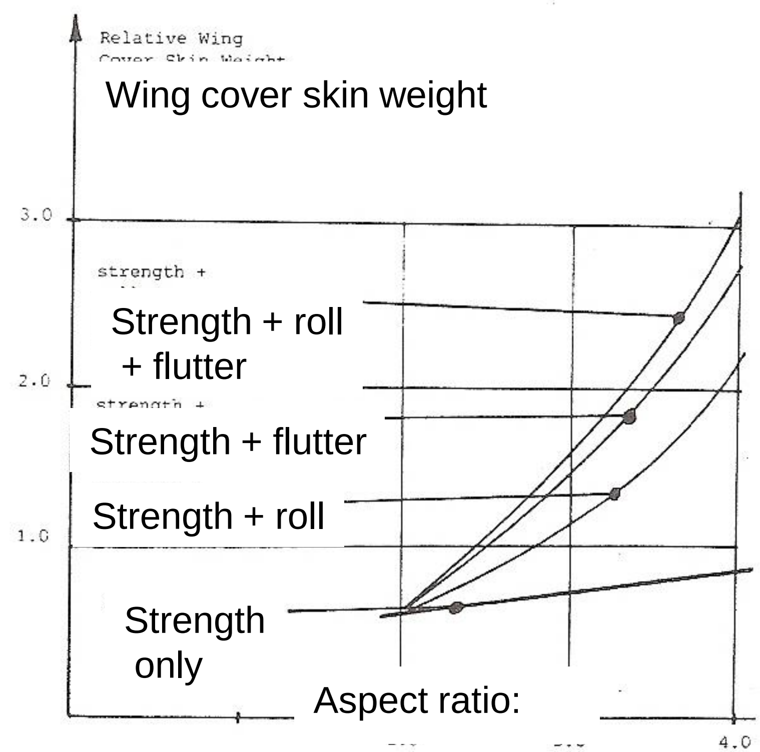


Taper ratio:

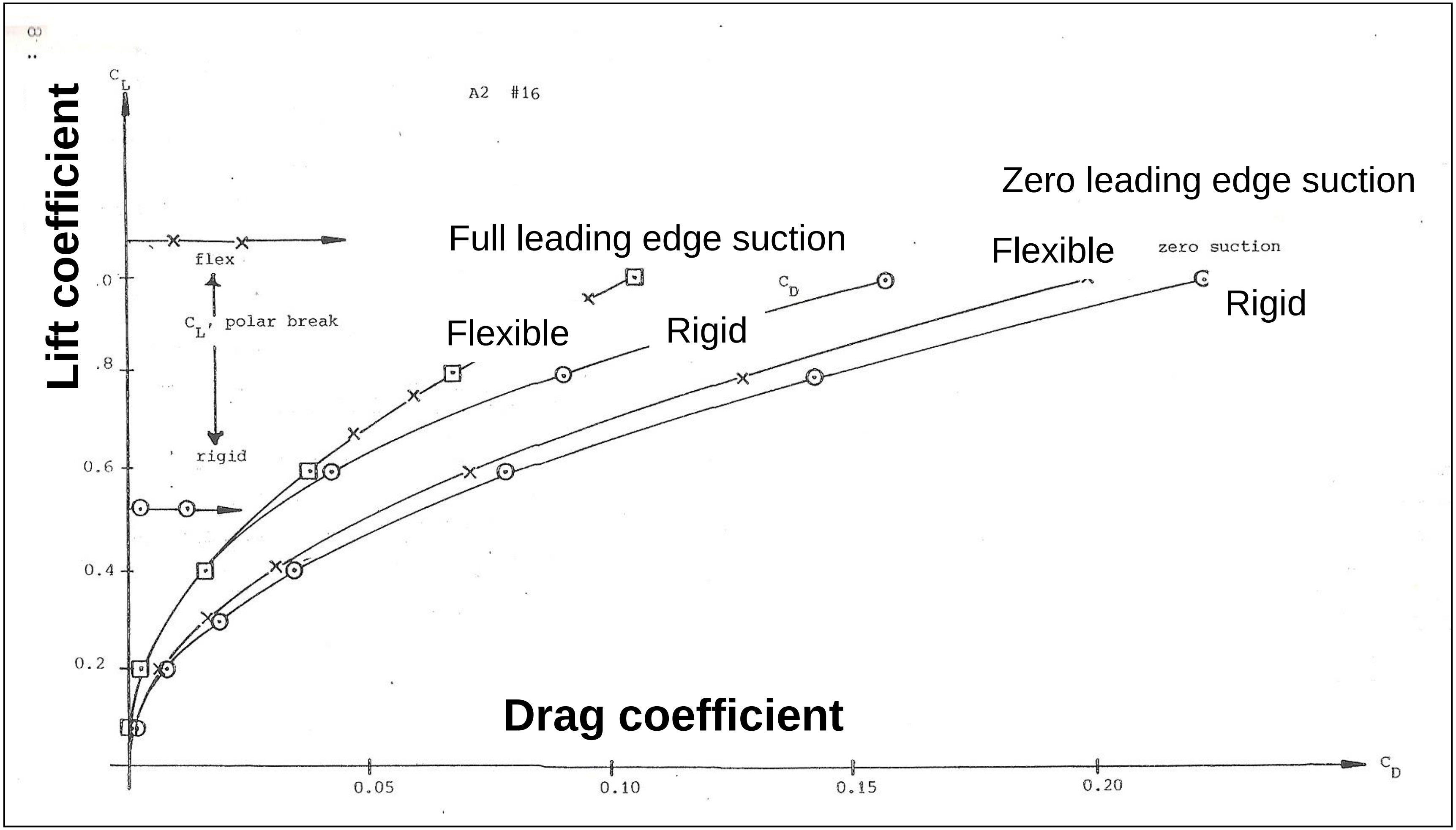


+ Thickness ratio

Typical result:



Additional capability:
Calculation of rigid and flexible drag polars



An essential issue for the Eurofighter wing design: roll performance at high dynamic pressure

Initial aeroelastic analysis showed only marginal roll rates (aeroelastic effectiveness near aileron reversal)

AND

Aeroelastic wind tunnel tests (at high speed) delivered much lower values than predicted by CFD analysis.

- Aeroelastic analysis for the “rigid” steel wind tunnel model showed a 50 % loss of effectiveness.
- Structural optimization for the wing skins.
- Refined control surface geometry.

The design then met the roll rate requirement – however with very high control surface hinge moment – causing additional torsion loads for the wing box and only at the cost of a very high actuation system power demand.

- Additional action: increase the required aeroelastic effectiveness constraint to get a smaller total mass (structure + actuation system).

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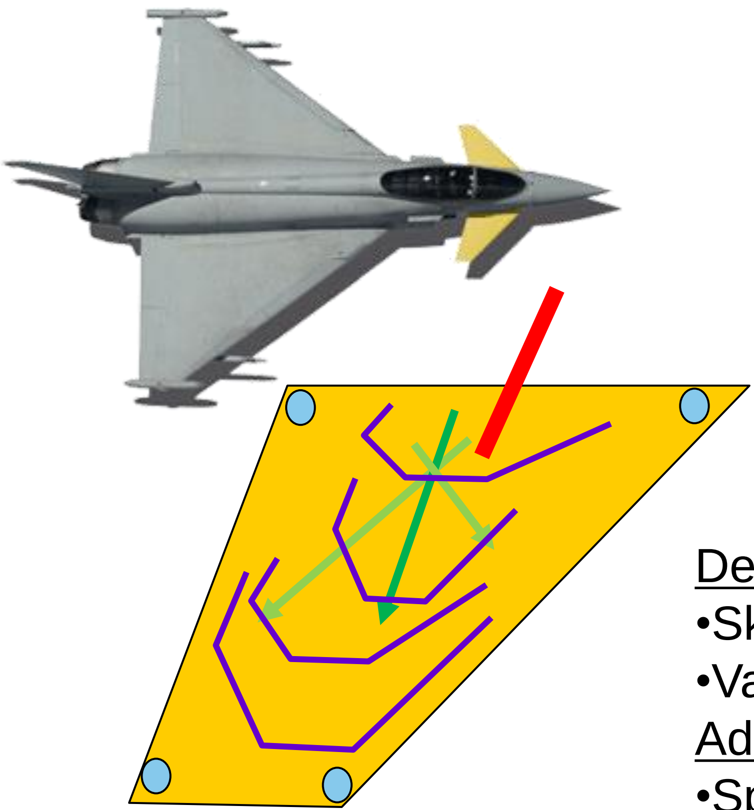
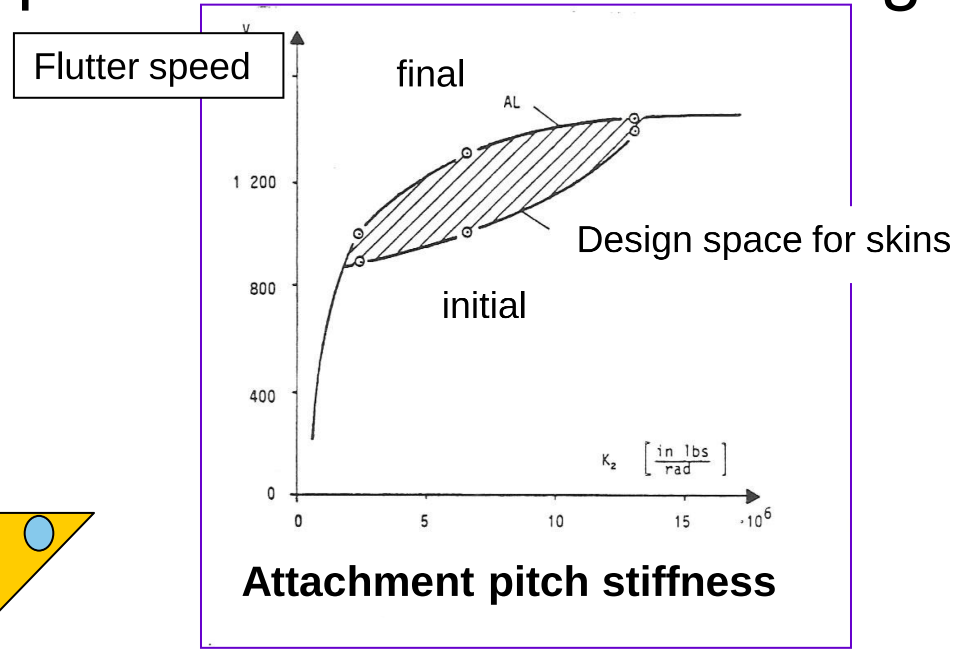
TSO application for an all-movable foreplane surface as an example for Aeroelastic Tailoring limitations





<u>Design variables:</u>

- Skin thickness and fiber orientation (3 layers)
- Variable masses for flutter

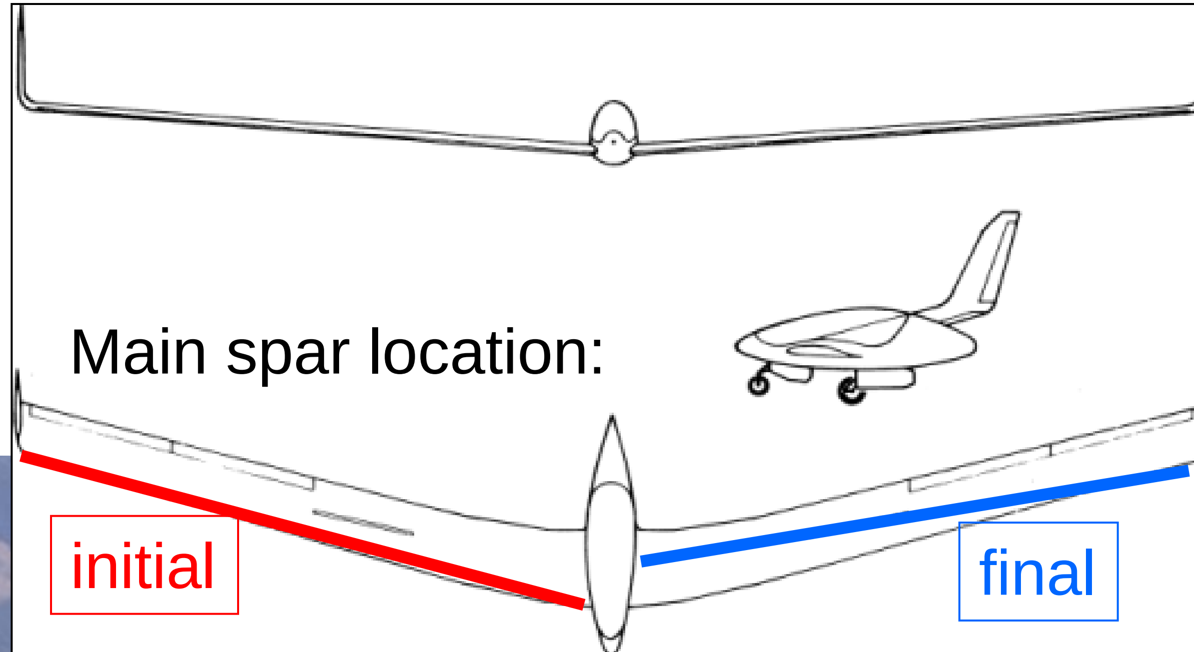
<u>Additional parameters:</u>

- Spigot location and sweep angle
- Attachment pitch and bending stiffness

SB-13 (Akaflieg Braunschweig): the first German aircraft with formal Aeroelastic Tailoring application (1984)

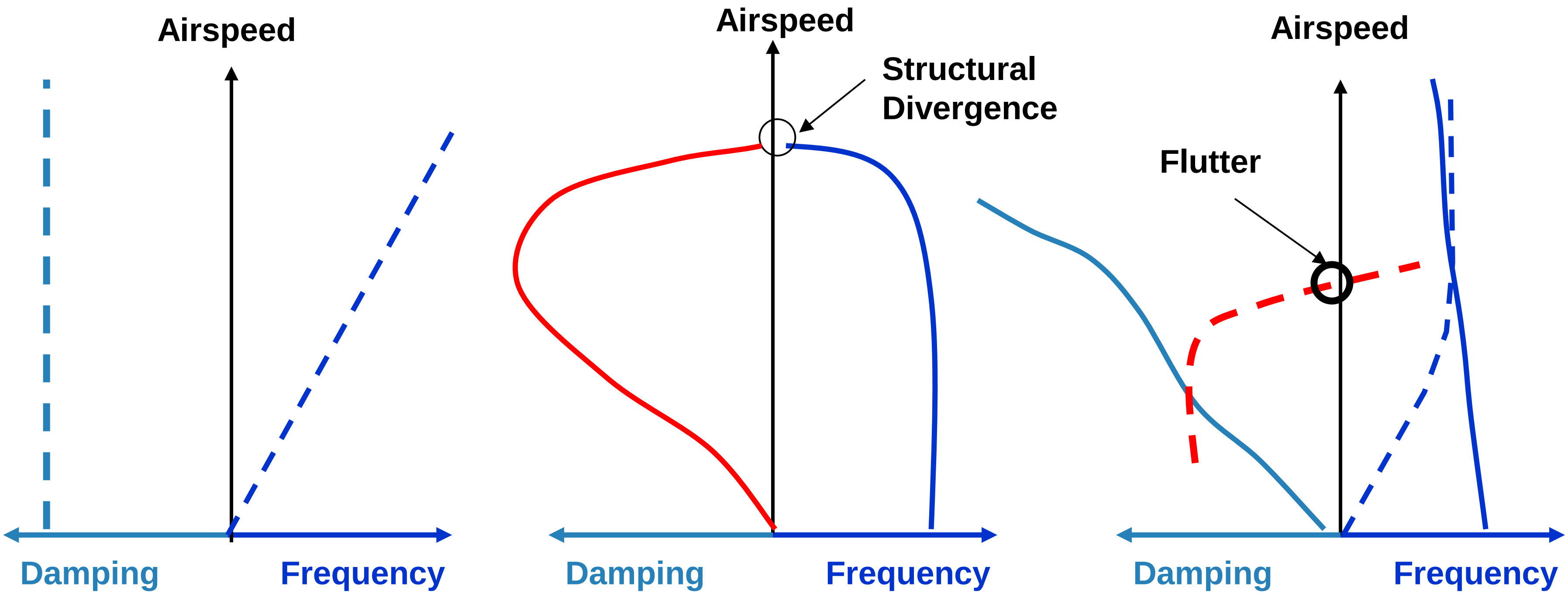
"Body Freedom Flutter" Instability

Flutter speed:
initial: 120 km/h
final: 280 km/h



Solution:
- Optimization tools (as "indicators")
- Simulation of free aircraft modes
- High modulus fiber spar caps
- Swept main spar (with external geometry modification).

SB-13: disciplinary and multidisciplinary treatment of a stability problem



Flight mechanics
(Short period mode)

Aeroelasticity
(1st bending mode)

Coupled analysis

Single-disciplinary approaches may or may not show potential risks or show a too optimistic picture

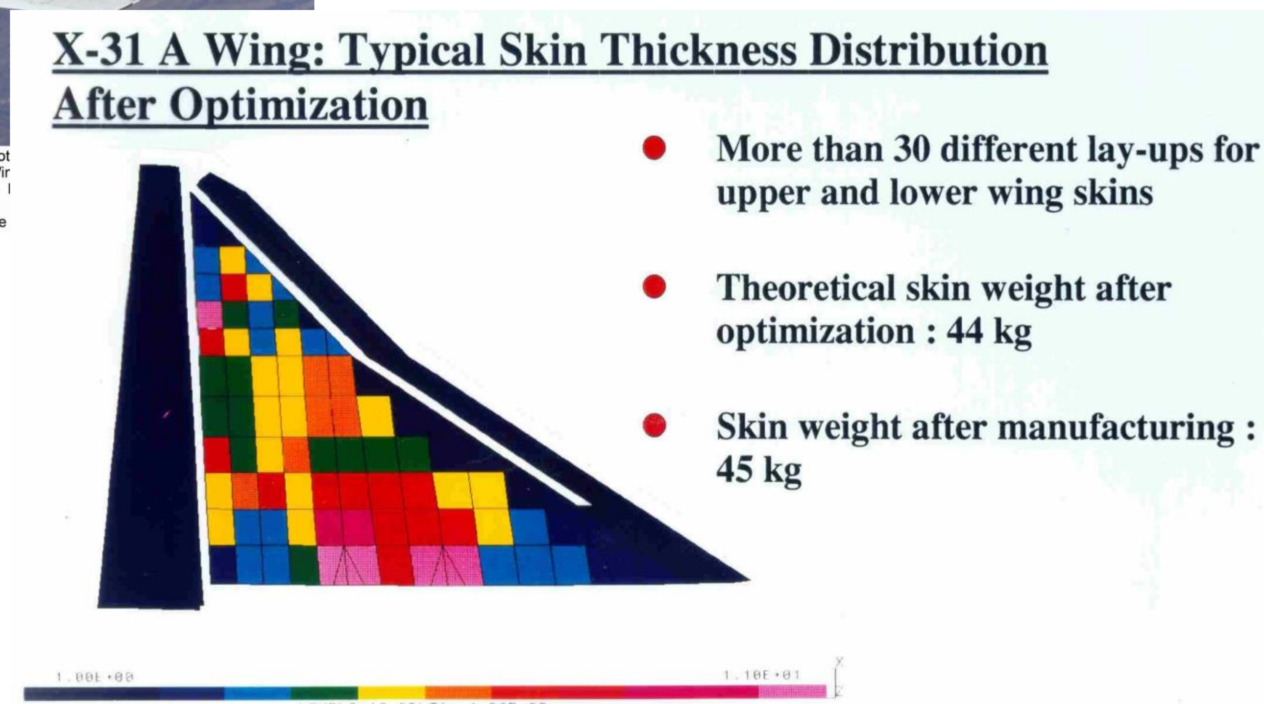
Some reasons to launch the new MDO tool *LAGRANGE* development in 1983

- More general capabilities than the wings-only features of FASTOP and TSO
- Needs from other divisions (space, helicopters, missiles) were included. The project was started at corporate level (also budget and core team).
- Compatibility with NASTRAN inputs was desired.
- Independence from external software vendors (high flexibility for adjustments).

So far, more than 120 person years were spent to develop and upgrade *LAGRANGE*.

X-31A wing design (1988):

- Strength and bucking
- Static aeroelasticity (constraints not active)
- Complex lay-up
- Buckling still with constant lay-up only (tool developmet started too late).



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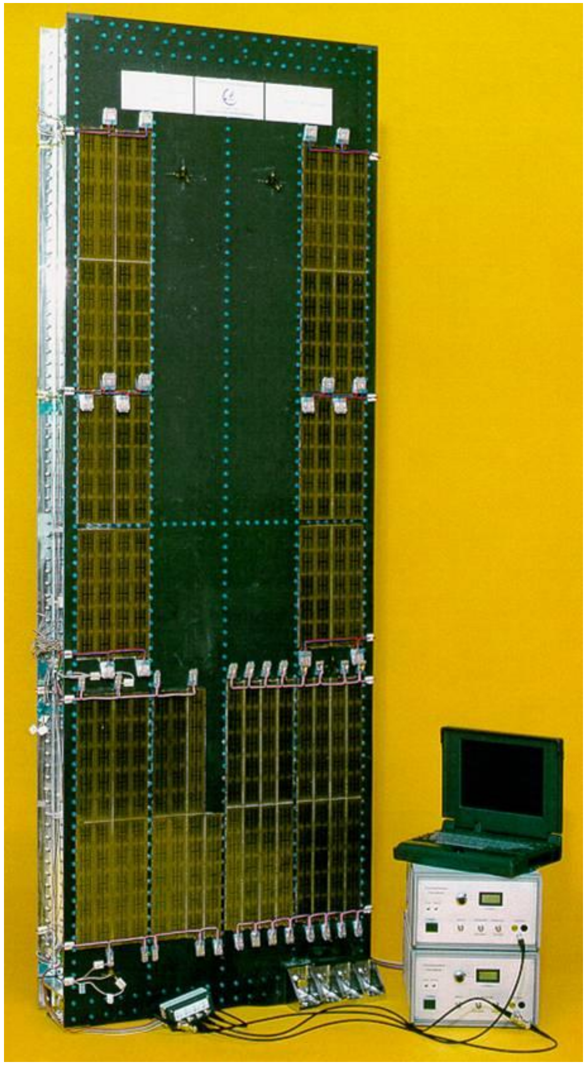
1990s *LAGRANGE* applications

- Hermes Spaceplane (structure, vibration levels on the internal equipment)
- Active Aeroelastic Wing Studies (applied to the Eurofighter wing)
  - Roll control with leading and trailing edges
  - Active materials effectiveness simulation in aeroelastic analysis
- Alternative manufacturing concepts simulation (example: resin transfer molding)
- Stealth demonstrator project FTT
- Trainer aircraft Ranger 2000
- Reduced size vertical tail with high aeroelastic effectiveness
- SHM: defect localization and sensor placement
- European research projects (higher order CFD, MDO, flying wing ("MOB")).
- **Fin buffeting load alleviation (full scale demonstrator with optimized placement and control of Piezo patches.)**



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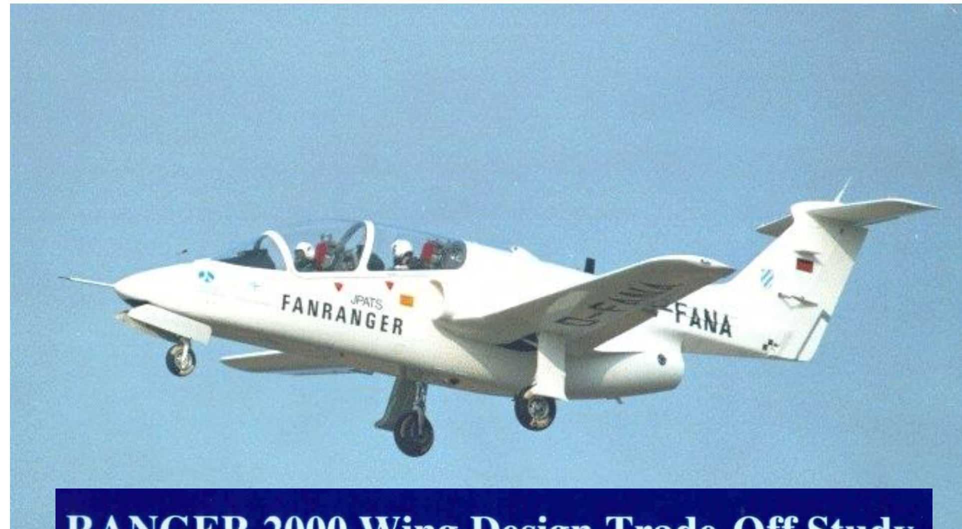
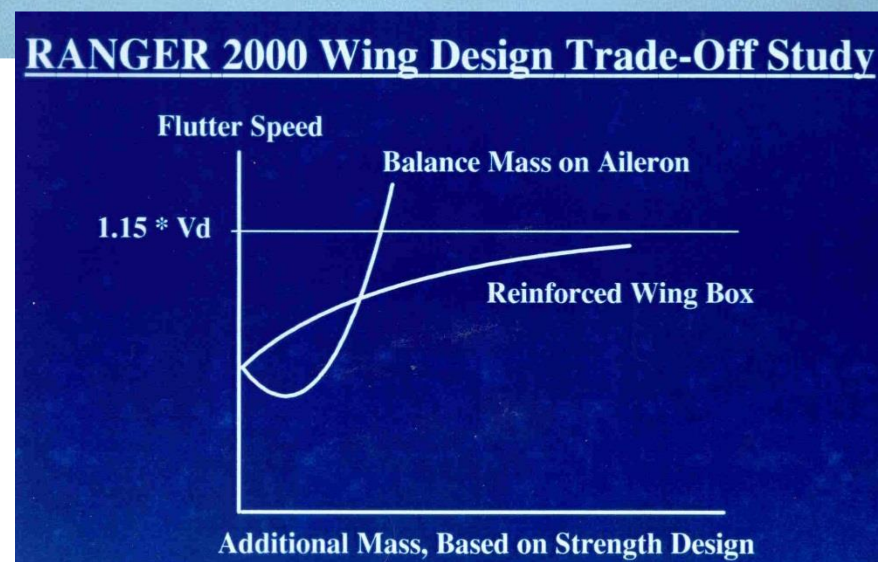
Ranger 2000 Training Aircraft
(Rockwell candidate for the US JPATS competition (1992-94)

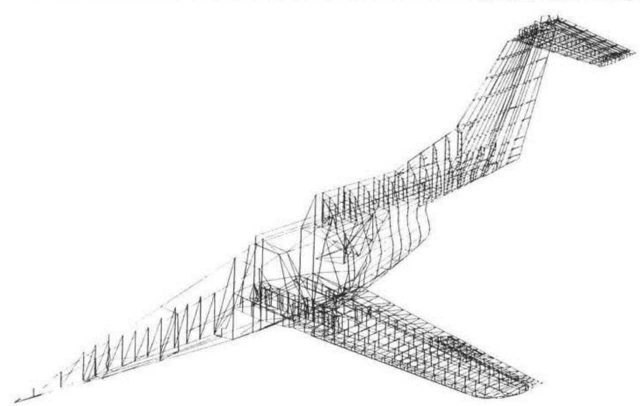
LAGRANGE was used rather late in the design process - mainly to determine the required mass balance for the control surfaces.

<u>Important feature:</u> adjustment of aerodynamic forces on control Surfaces for flutter.





RANGER 2000 Training Aircraft



Finite Element Model for Aeroelastic Design

MDO applications for aerodynamic drag and loads reduction

EC project “Active Aeroelastic Aircraft Structures” (3AS), 2002-2005:

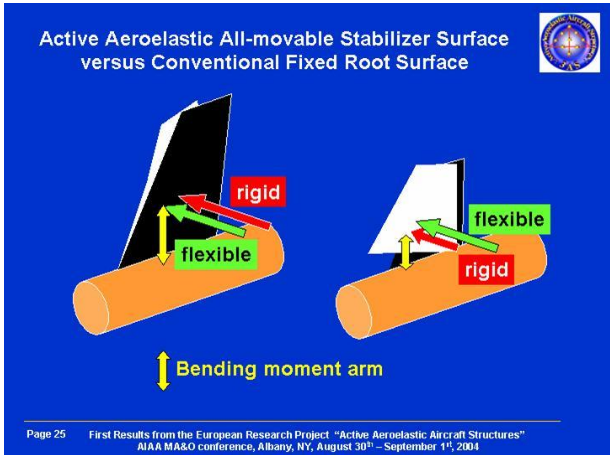
- Flexible wing shape control by new aerodynamic devices:

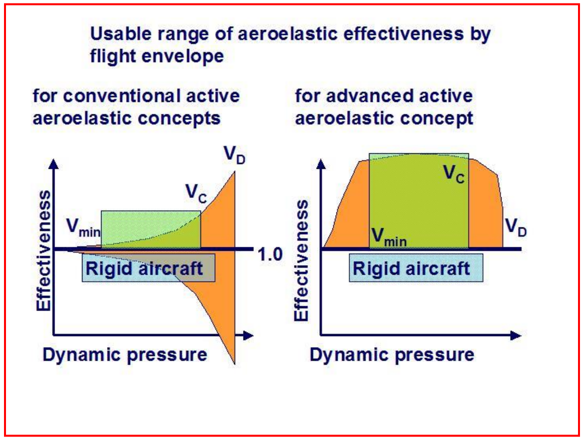
  Tasks: optimum position, shape, and size of the control devices.

- All-movable aerodynamic surface with reduced size by an adaptive stiffness attachment concept.

  Tasks:

  - stabilizer shape and size
  - attachment location
  - attachment stiffness (vs. dyn. pressure)





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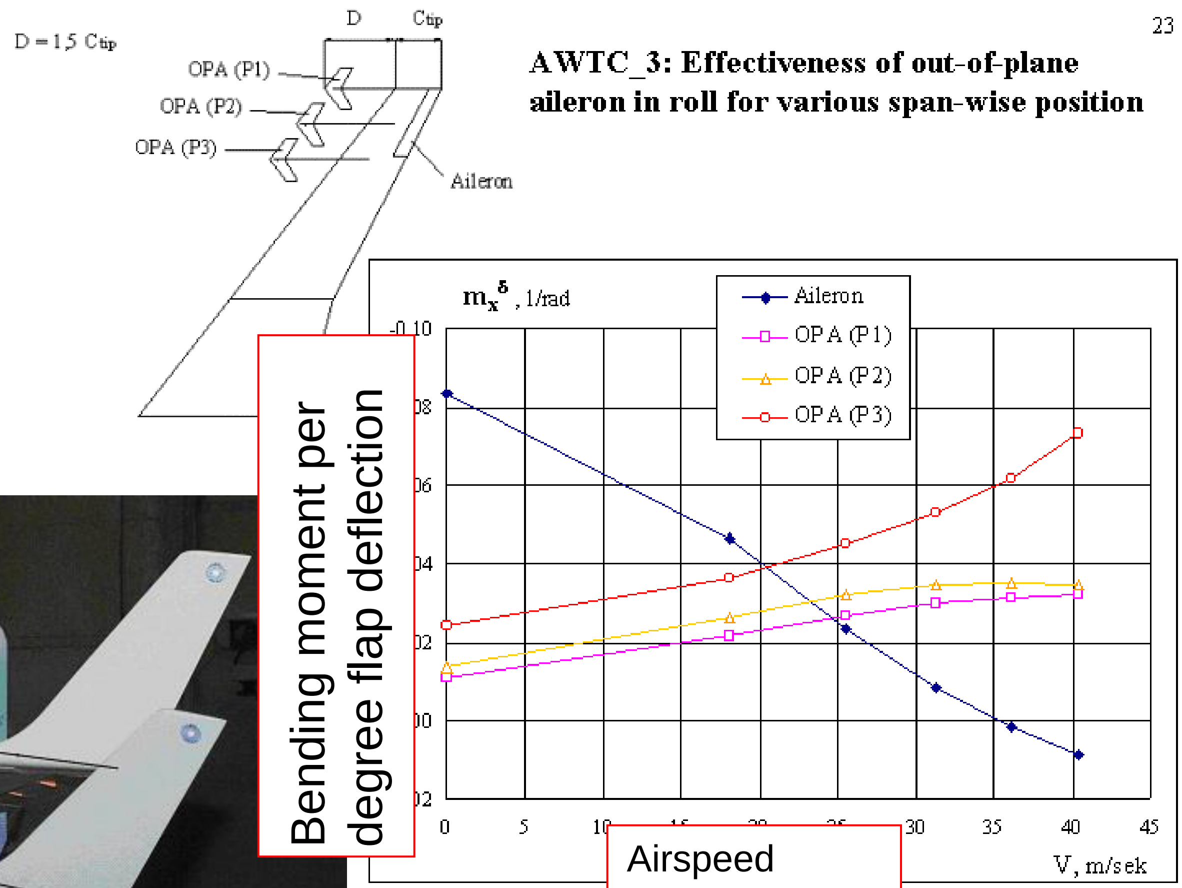
External control surface concept in 3AS

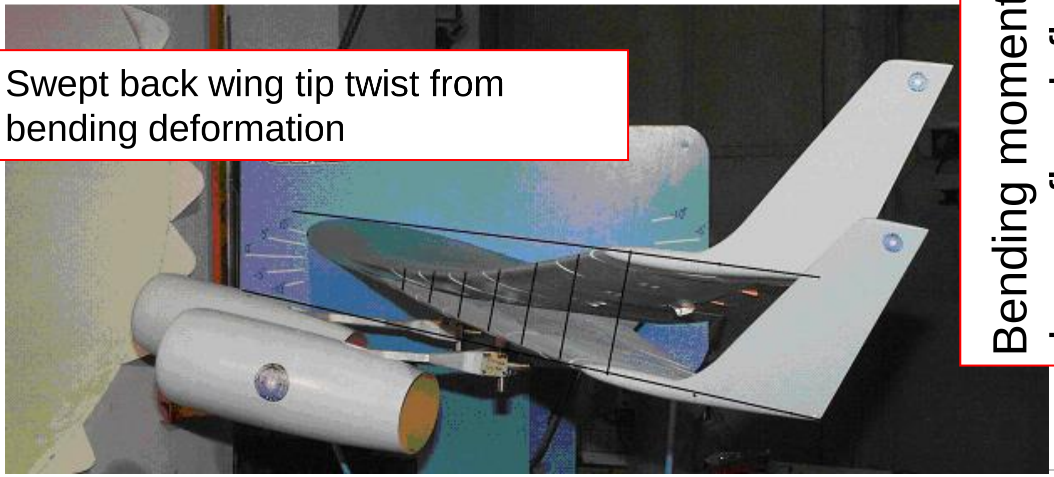
… used to adjust the flexible shape and for active load alleviation



Bending moment per degree flap deflection

Airspeed

Swept back wing tip twist from bending deformation



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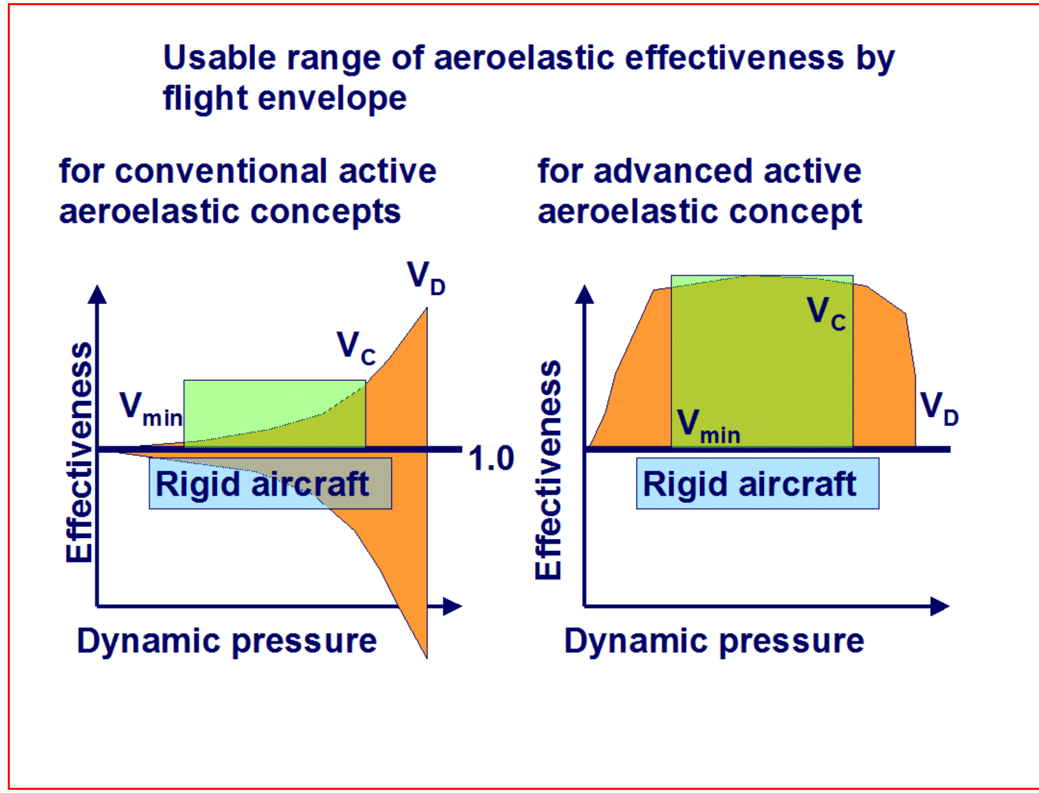
3AS: All-movable aerodynamic surface with variable stiffness attachment



<u>Advantages:</u>

Smaller stabilizer surface (2/3) with high effectiveness at all speeds.

- Less drag
- Reduced mass
- Reduced loads for the fuselage
- Mass reduction at the tail (good for the c. g. location)

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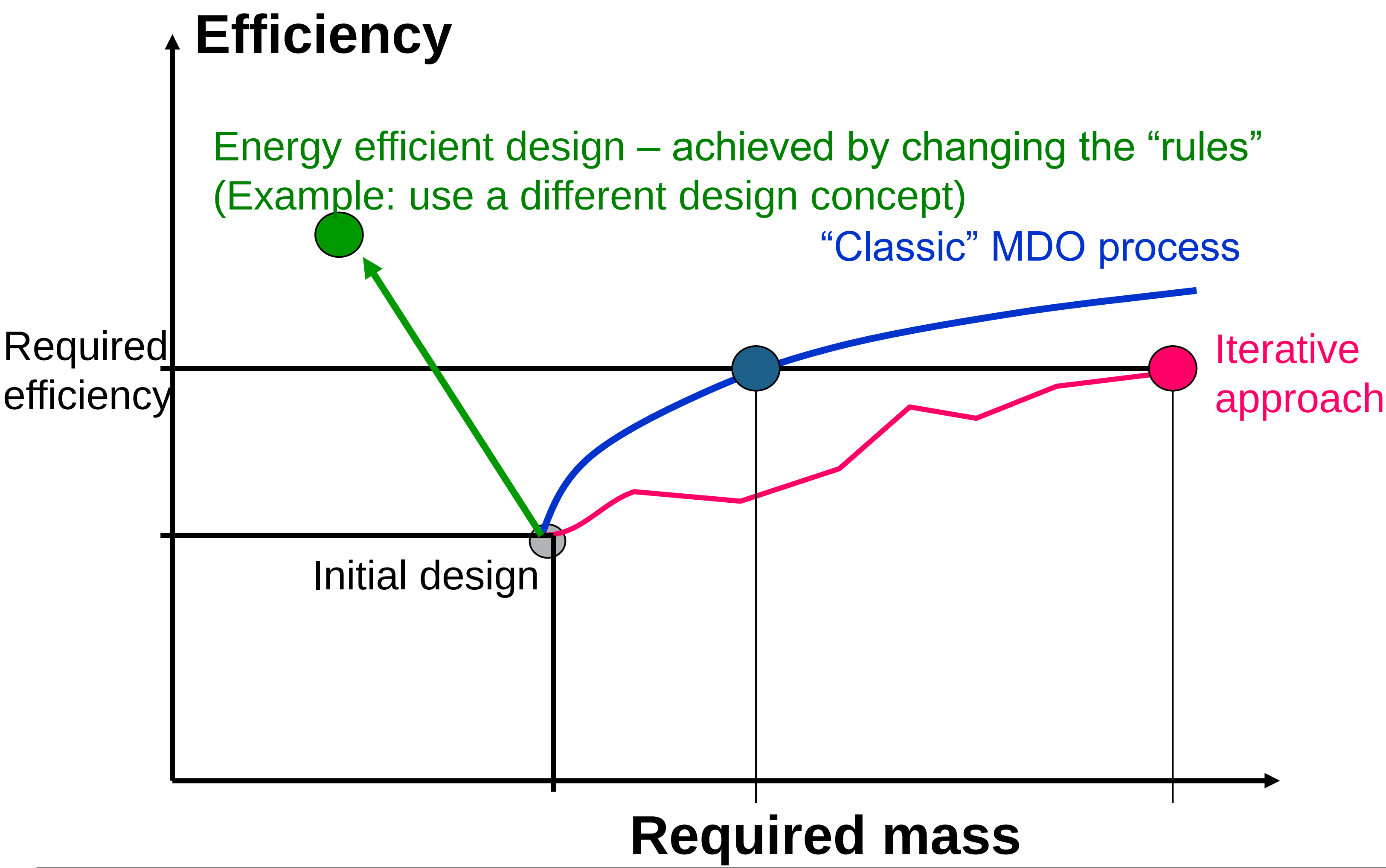
Different approaches to achieve the desired performance and energy efficiency as a new objective



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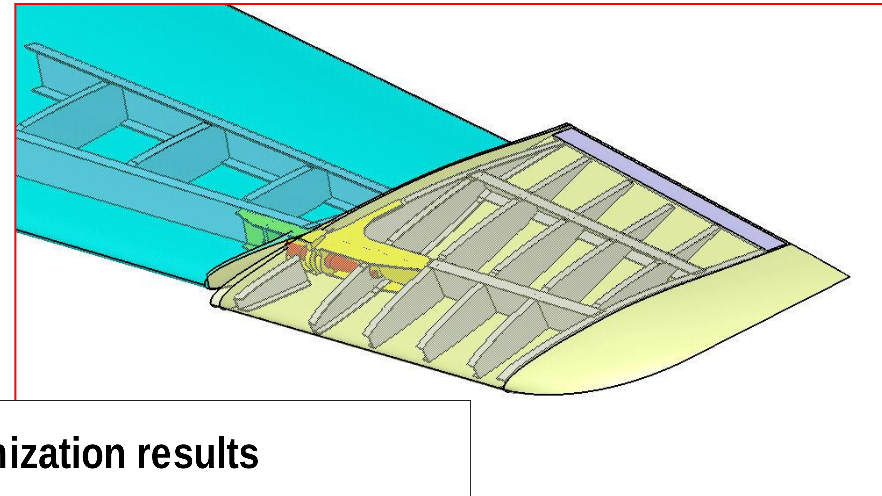
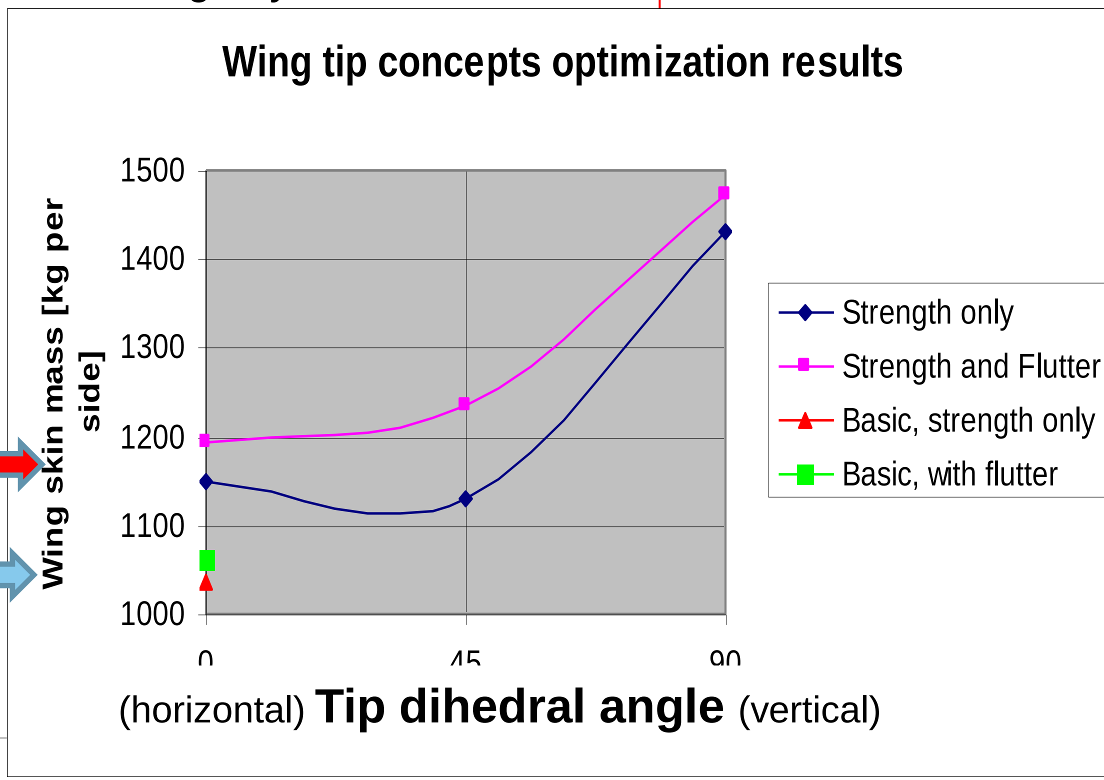
Adaptive wing tip design studies (started in 2005):

- Passive solution, allows high aerodynamic efficiency at low structural weight.
- Low aeroelastic effectiveness of the tip provides efficient load reduction.
- Optimum aerodynamic shape at cruise conditions.
- Balanced, feasible design by MDO.

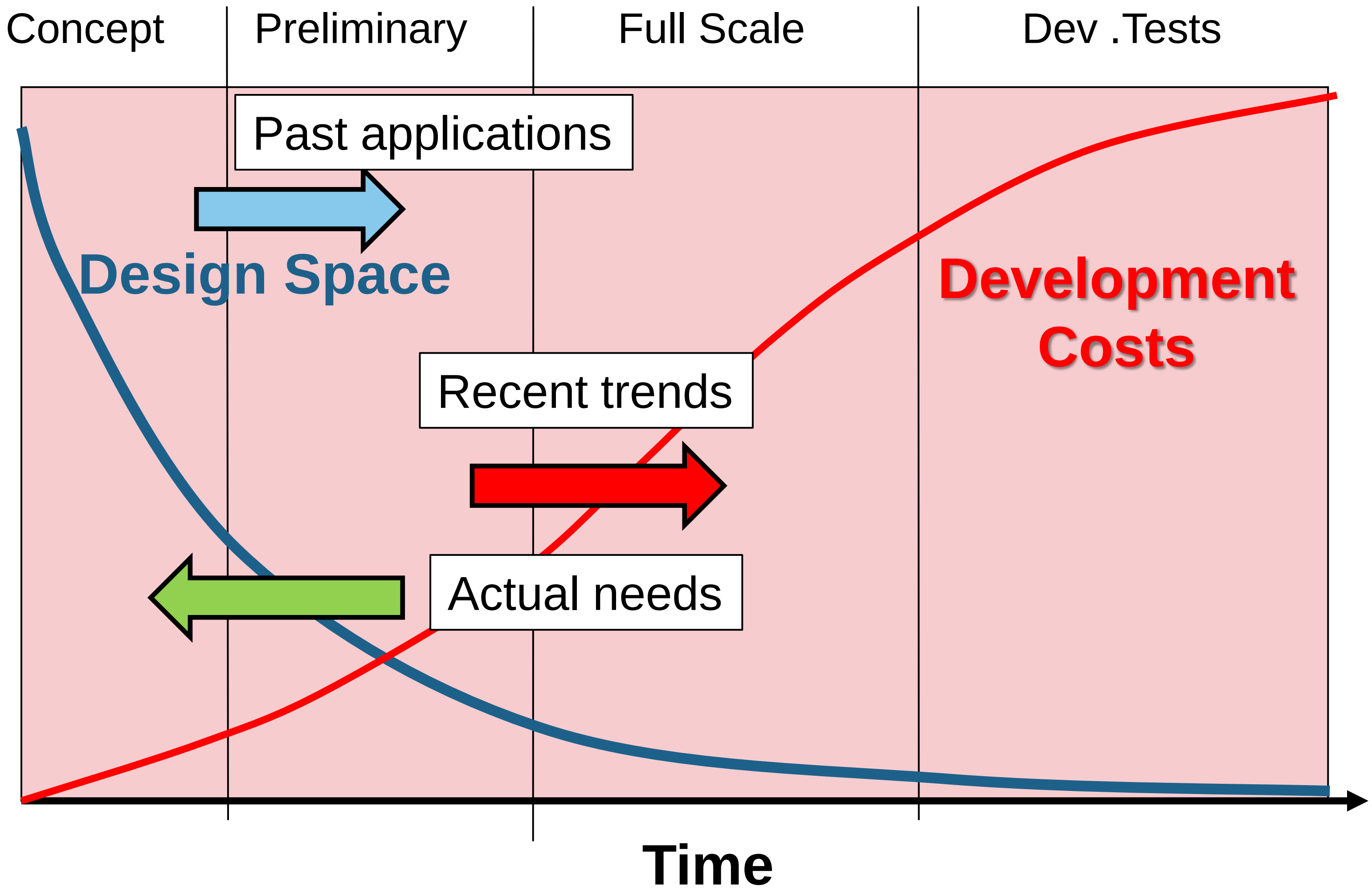


Wing with fixed tip

Short wing



Where MDO should be applied and where it actually is applied today



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Why are efficient MDO methods not applied earlier in the design process?

- Tools are getting more and more complex. Specialists are required to use them (and interpret the results).
- Too complex analytical models are built too early (by specialists from the individual disciplines).
- Analysis efforts are too high for early project phases (time, budget).
- Models are not suitable for formal optimization
  - Not complete
  - The wrong elements are used by the optimizer.
- Too many and too complex tools for the preparation and results evaluation.

… and how can this situation be improved?

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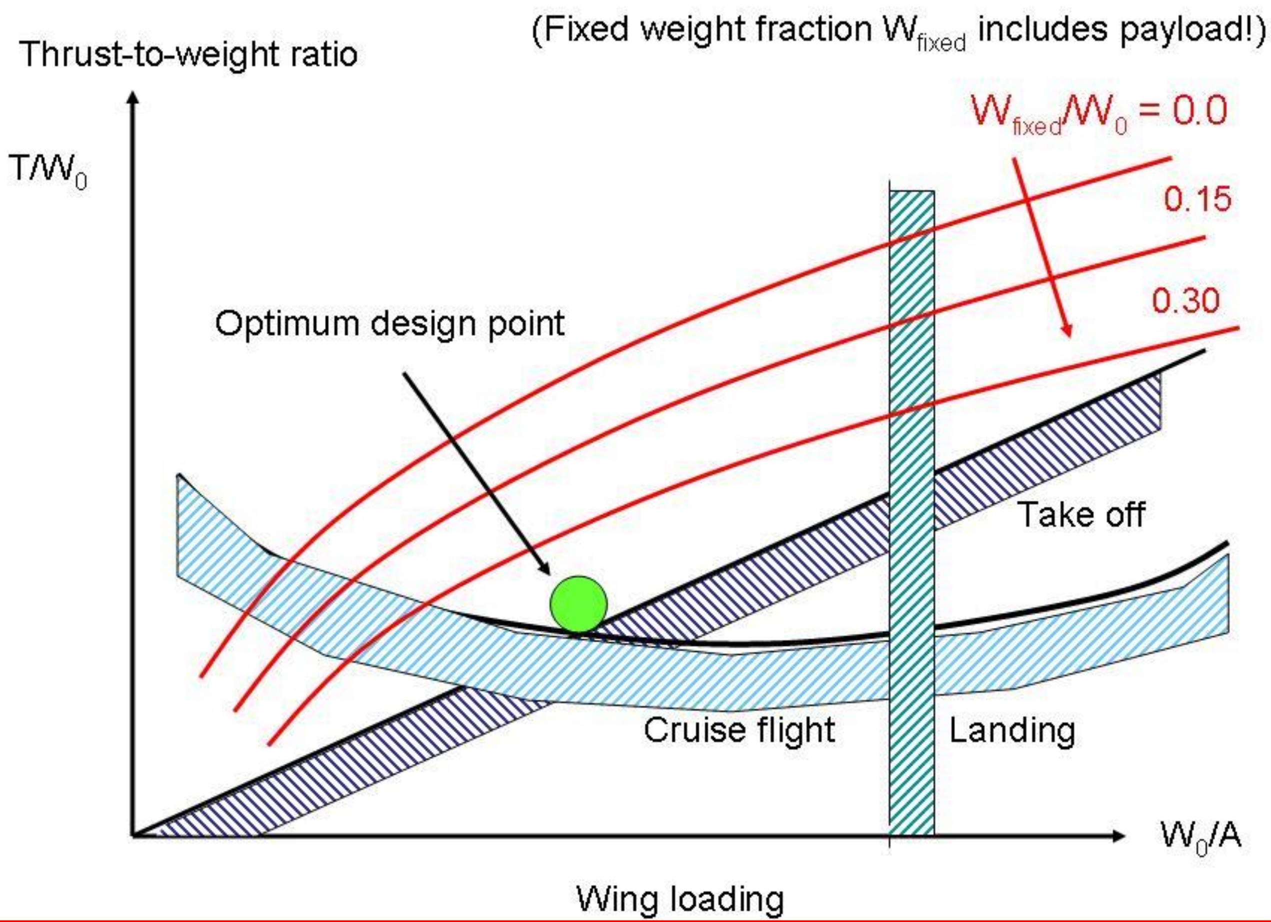
Typical MDO process in conceptual design



This global “sizing” process is based on empirical data (from existing airplanes) for the required structural mass!

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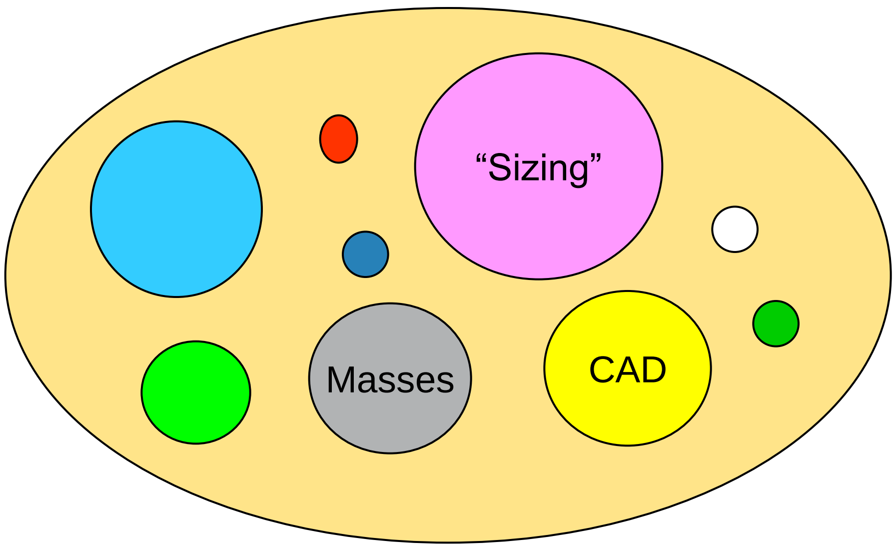
Main tools and models for conceptual design and for the "dicsiplinary design world"

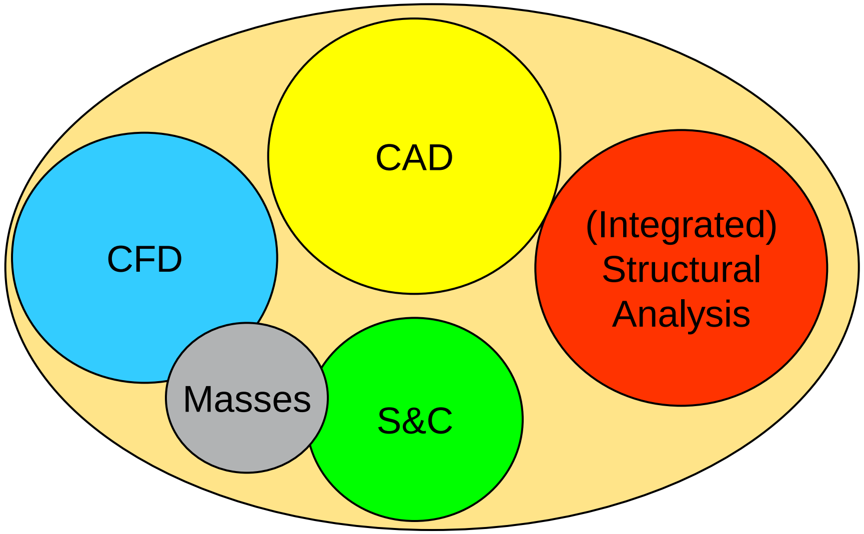
Conceptual Design World



Many tools, simpler models, handbook methods

Structural analysis does not exist!

"Specialists' Disciplinary Design World°



Fewer, but more complex and sophisticated model

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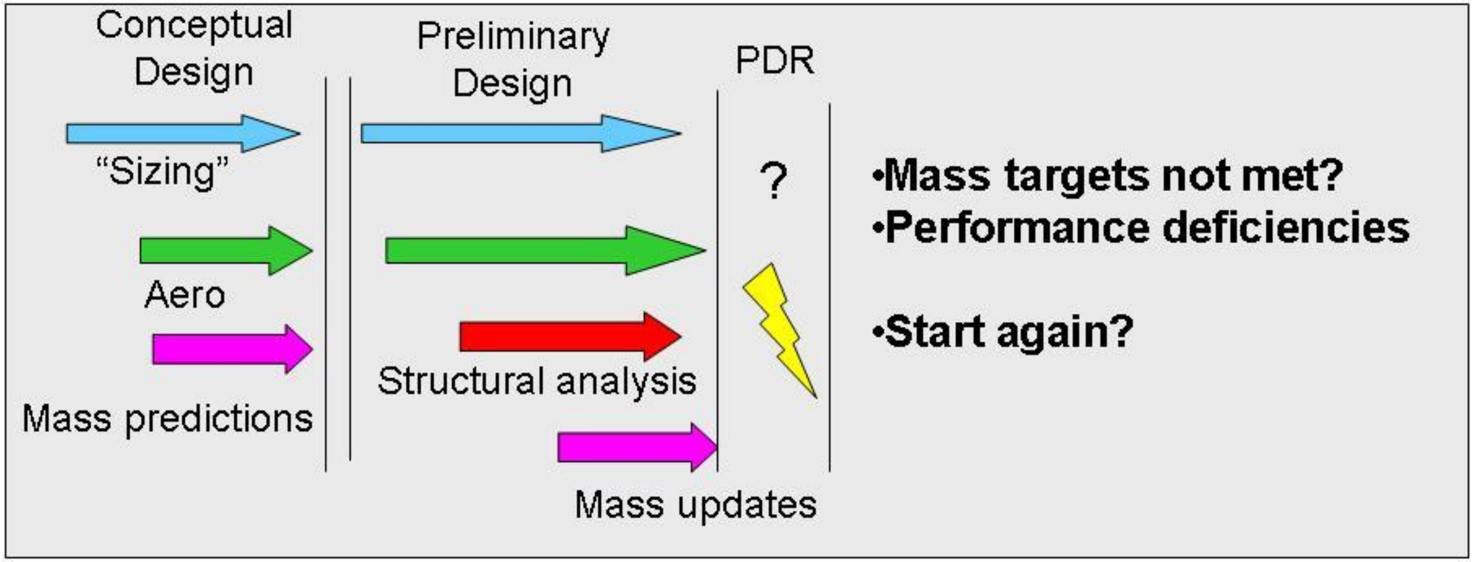
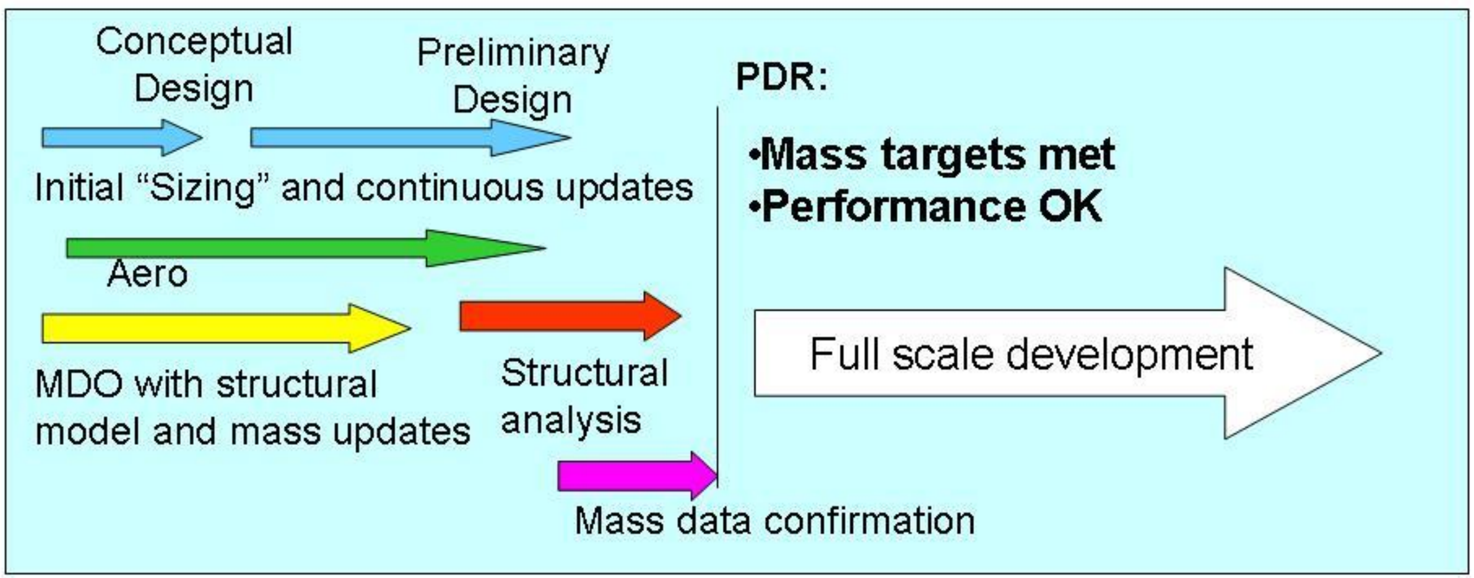
Typical situation and how it can be avoided





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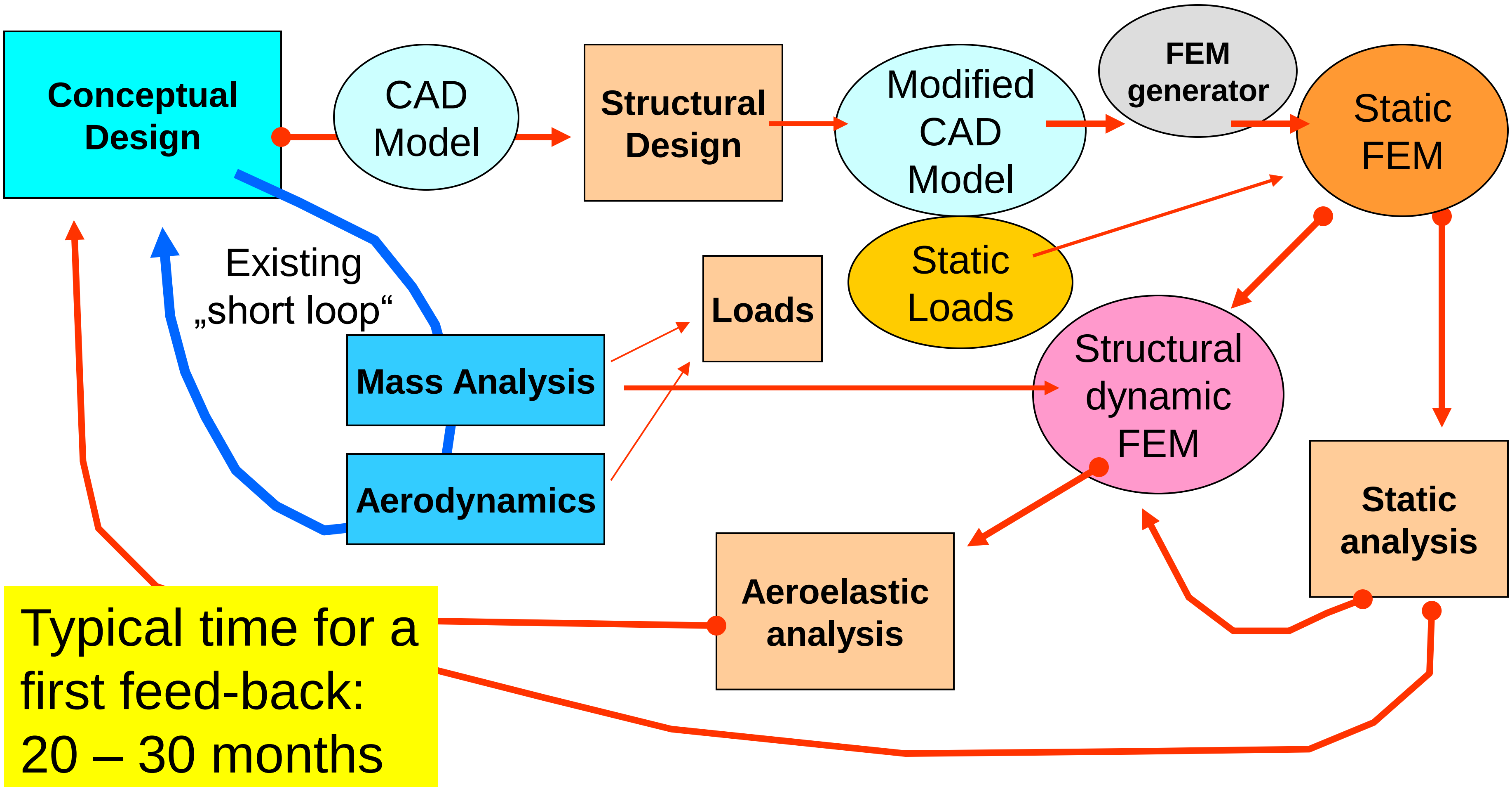
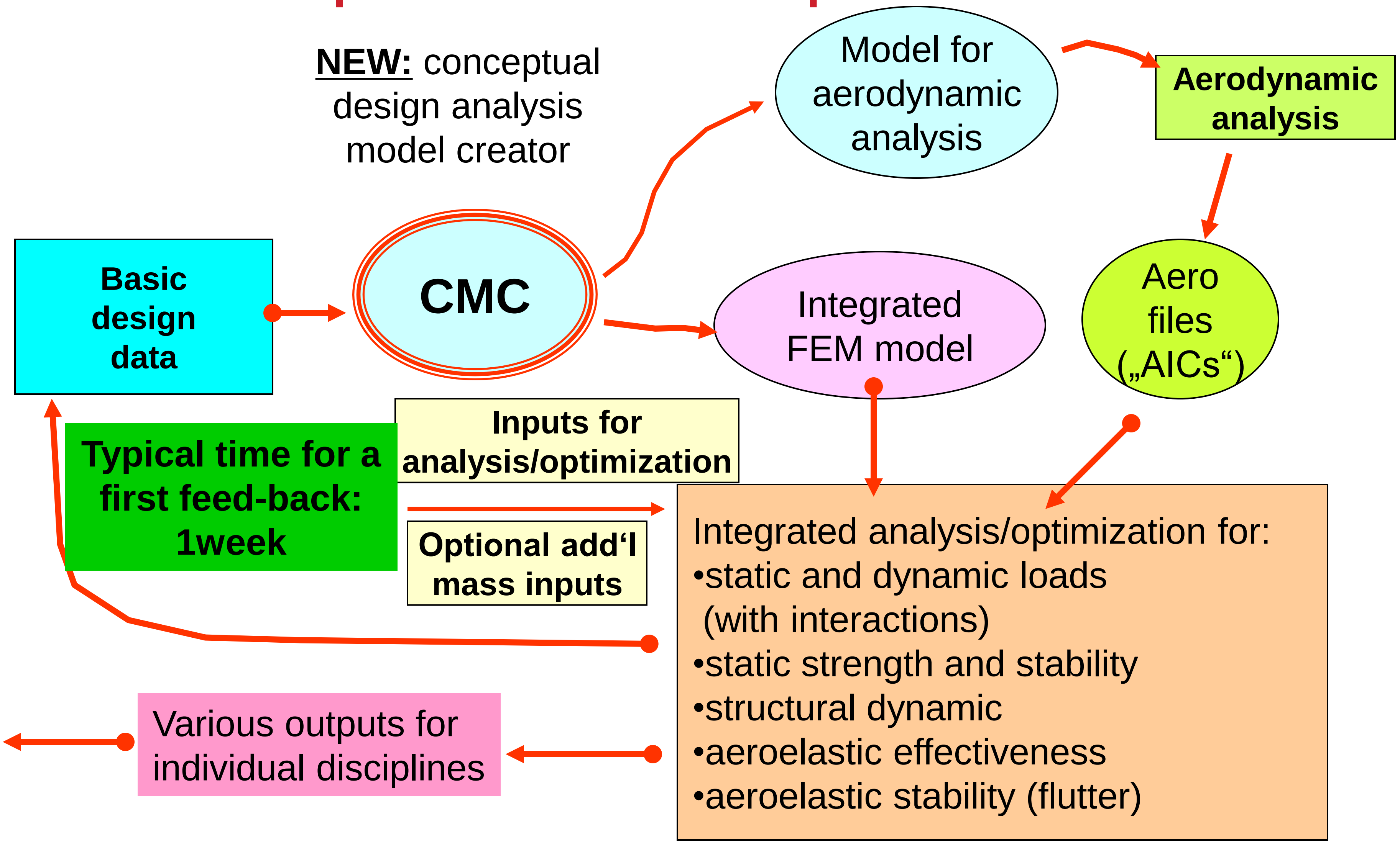
Old Approach for the Air Vehicle Analysis Model Creation and Analysis Tasks



Target: Reduce the time for a first iteration to 2 to 3 months

Essential steps for the new MDO process

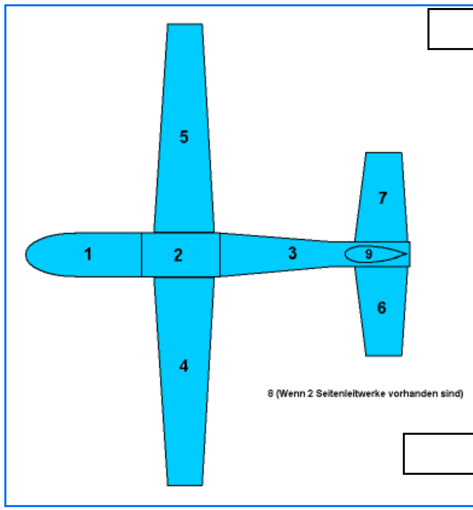


Target time for a complete concept evaluation/optimization: 2 to 3 months

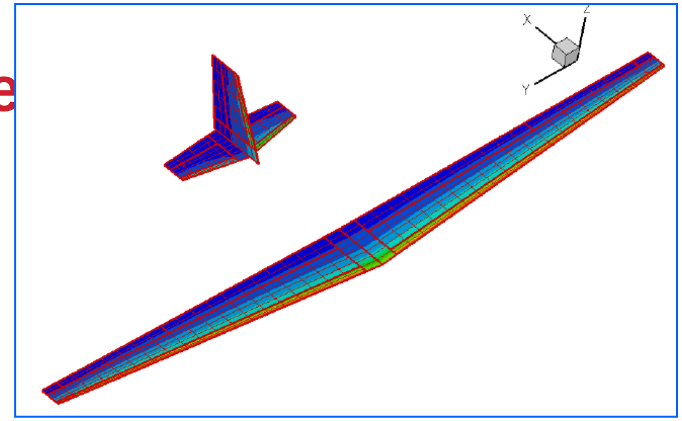
New Approach at CASSIDIAN: Fast creation of analytical models

without the need for a CAD mode

Input:
very few data by excel

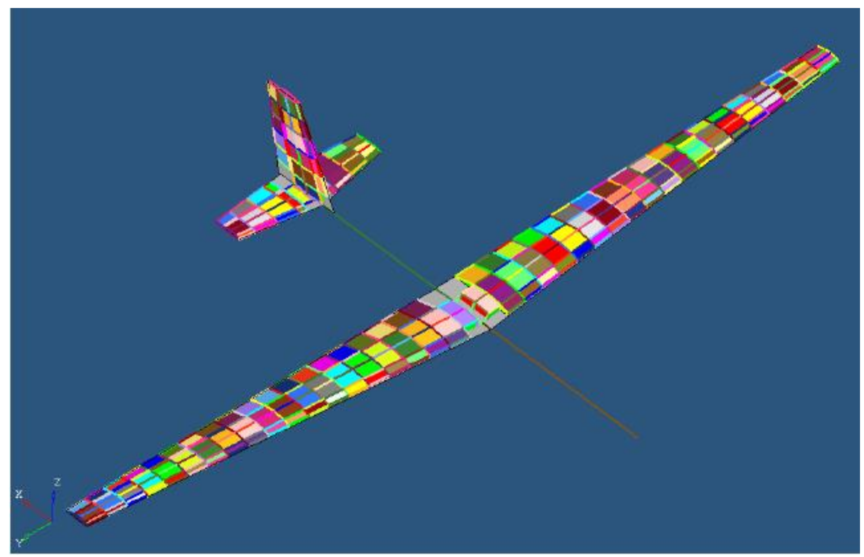


Aero Models
(steady & unsteady)



+ Coupling

+ Masses



FEM for:

- Aeroelastic-trimmed (or rigid) load cases
- Static strength and stability (buckling)
- Dynamic gust response
- Aeroelastic effectiveness
- Flutter stability

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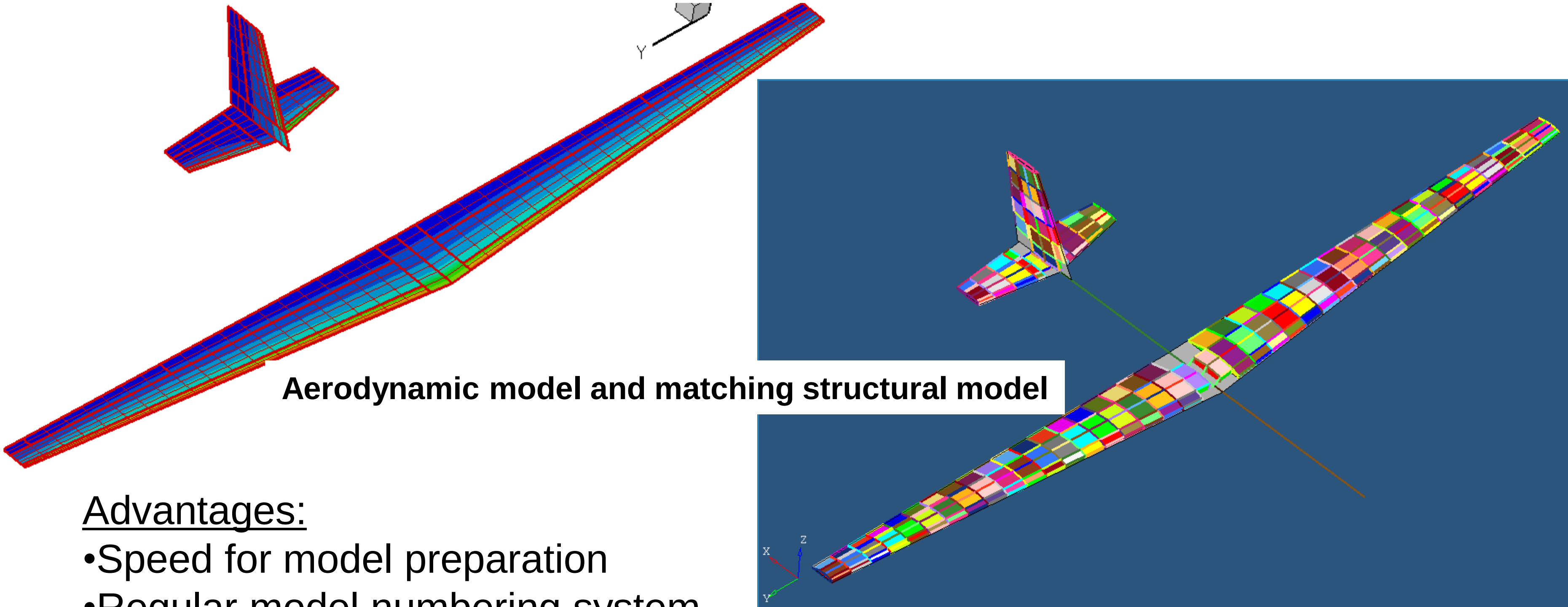
Example from the new MDO model creation process



Aerodynamic model and matching structural model

<u>Advantages:</u>

- Speed for model preparation
- Regular model numbering system
  - the user gets quickly familiar with it
  - it remains the same after modifications (model generator tools create always a new system)
- The model’s architecture represents typical aircraft light weight structural designs (which can be adjusted by the user to actual needs or design concepts
- High speed for optimization

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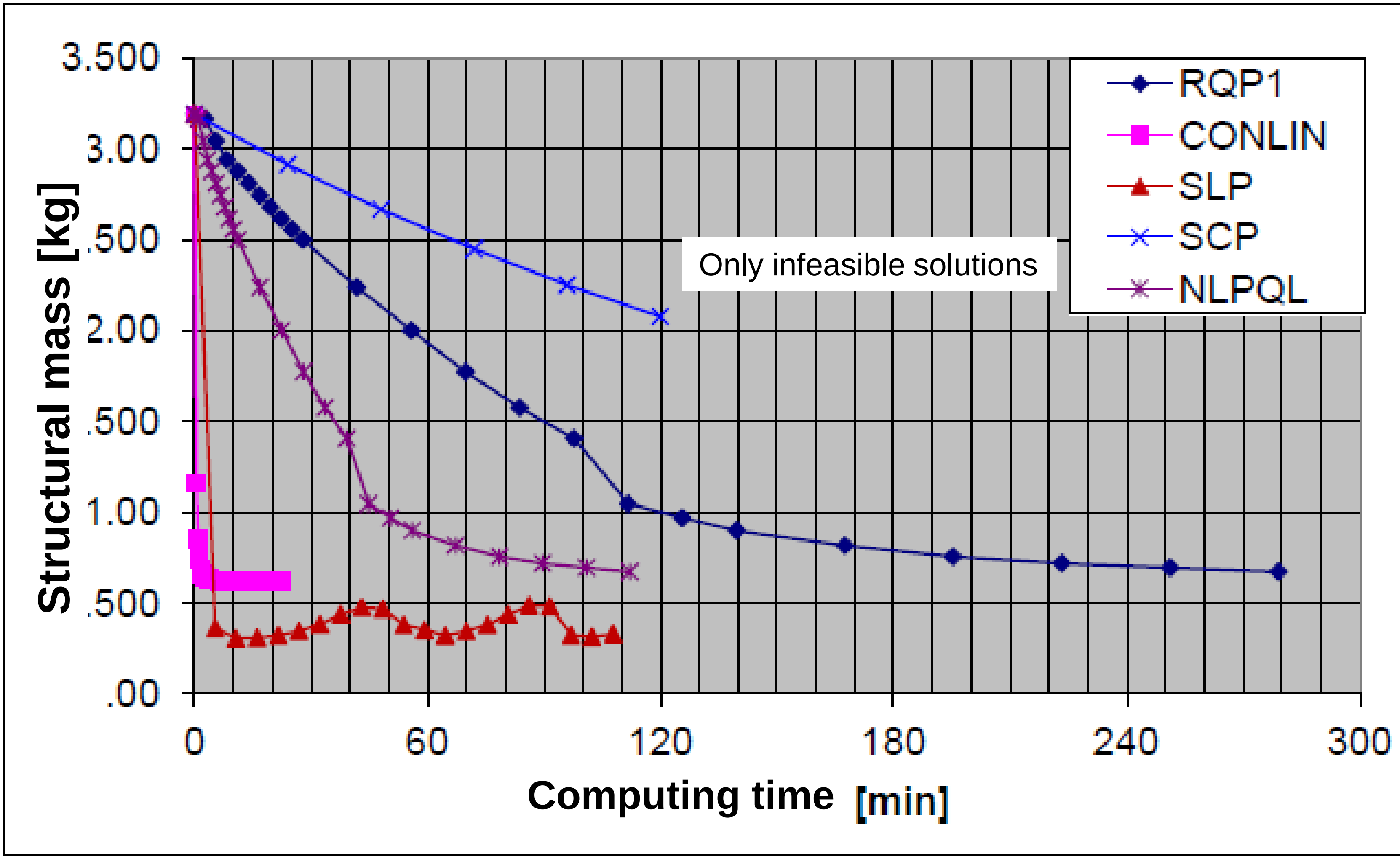
The Importance of proper optimization algorithms



The role of a multi-disciplinary mindset for innovations:

Many **innovations** are **based on** new combinations of **existing technology**. Some recent examples:

- The Tesla Motors all-electric cars have a conventional steel body and use laptop batteries. (Superior range and safety) vs.
  - BMW i3 with a carbon composite body and new batteries
  - B787 batteries
- SpaceX reusable rockets are based on existing technologies (like active control of unstable airplanes) vs.
  - Spaceplanes and Space Shuttle concepts
  - Upgraded rockets

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Summary

Formal MDO methods are very efficient tools to:

- Find a feasible (“the best”) solution for a set of design requirements.
- Investigate the impacts from the magnitudes of individual requirements on the result.
- Quickly modify the (initial) design boundary conditions in a favorable way (based on previous results).
- Evaluate optimization results by:
  - Interpretation of the mathematics behind the solution.
  - “Engineers’ alternatives.
- Avoid delays and additional costs from redesign efforts.

- **They should never be looked at as automation tool that delivers perfect solutions!**
- **It will always be the engineers: how they set up the models, interpret results, and make decisions.**

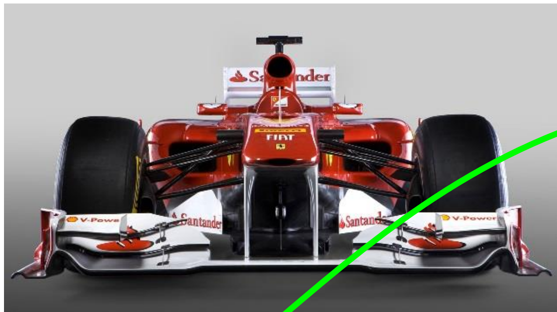
Personal conclusions after 33 years with MDO (I)

- Keep it simple! (and make it even simpler after a while!)
  - Models
  - Methods
  - Solutions
- Don’t trust the first results
  - especially when they are optimistic (“optimizers” are very smart - but in a mathematical sense, not technical)
  - but also when they do not meet your expectations
- Do not rely on previously successful solutions

  The new problem may need other solutions (example: classic aeroelastic tailoring from fighters applied to high aspect ratio wings)
- Try to think “outside the box” more often!

Personal Conclusions (II)

It sometimes looks like the automobile industry is ahead:

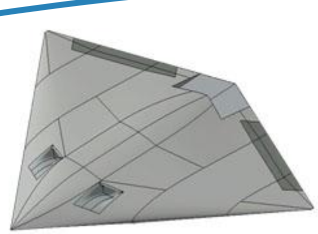


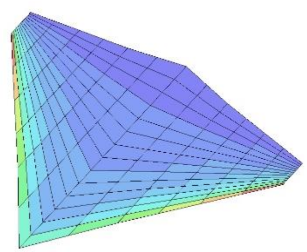
Winter break for a completely new car

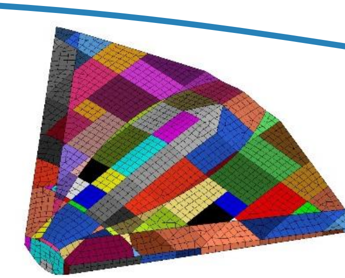
2 weeks between the races!

TIME (weeks)

Several months for the first analysis model preparation!







CONCLUSION: We have to catch up with cars again in aeronautics!

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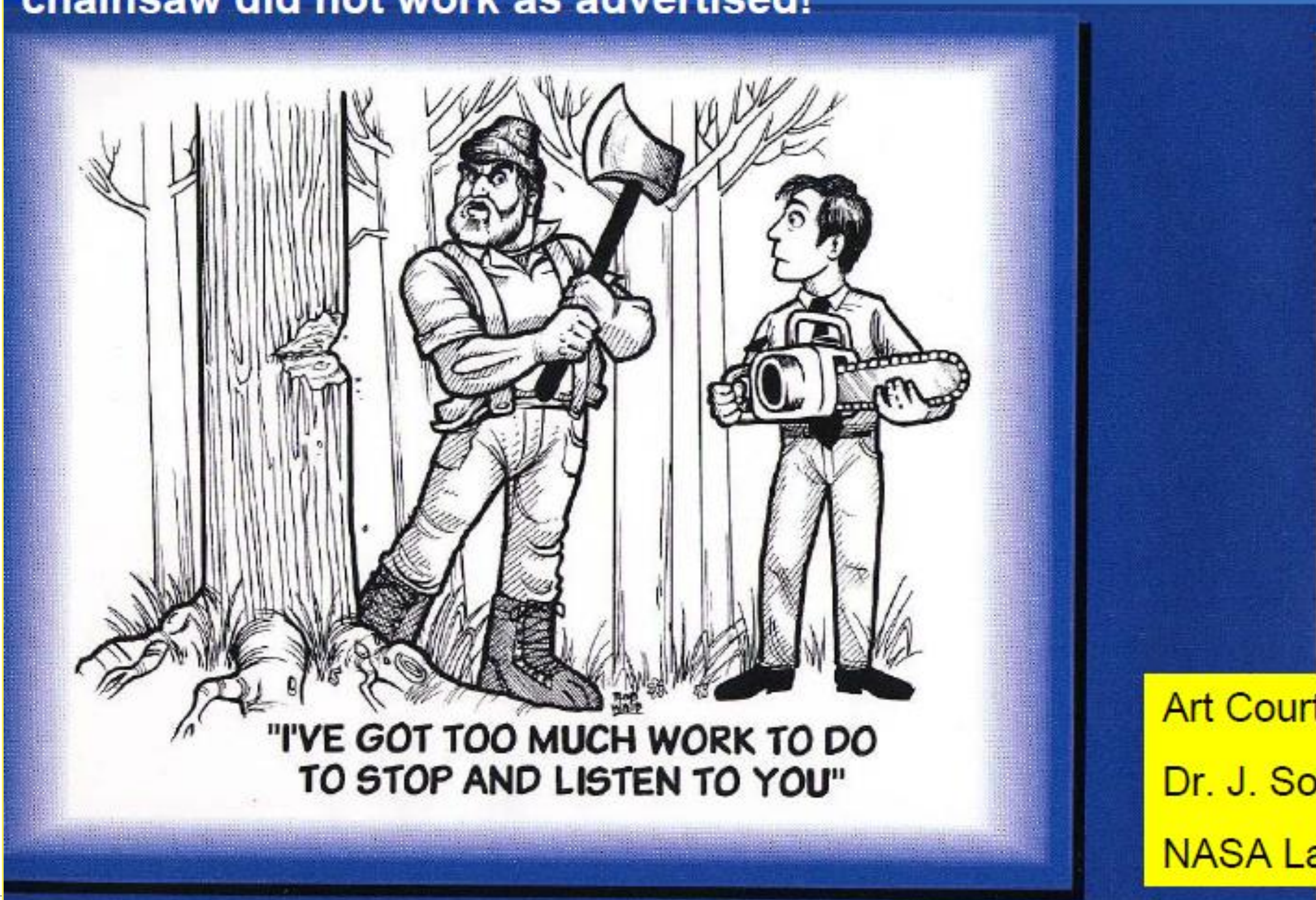
… and always keep in mind:

Selling MDA and MDO is hard because some assembly and development is required. Also on several past occasions the chainsaw did not work as advertised!



Art Courtesy of
Dr. J. Sobieski
NASA Langley

Thank you
for your attention!