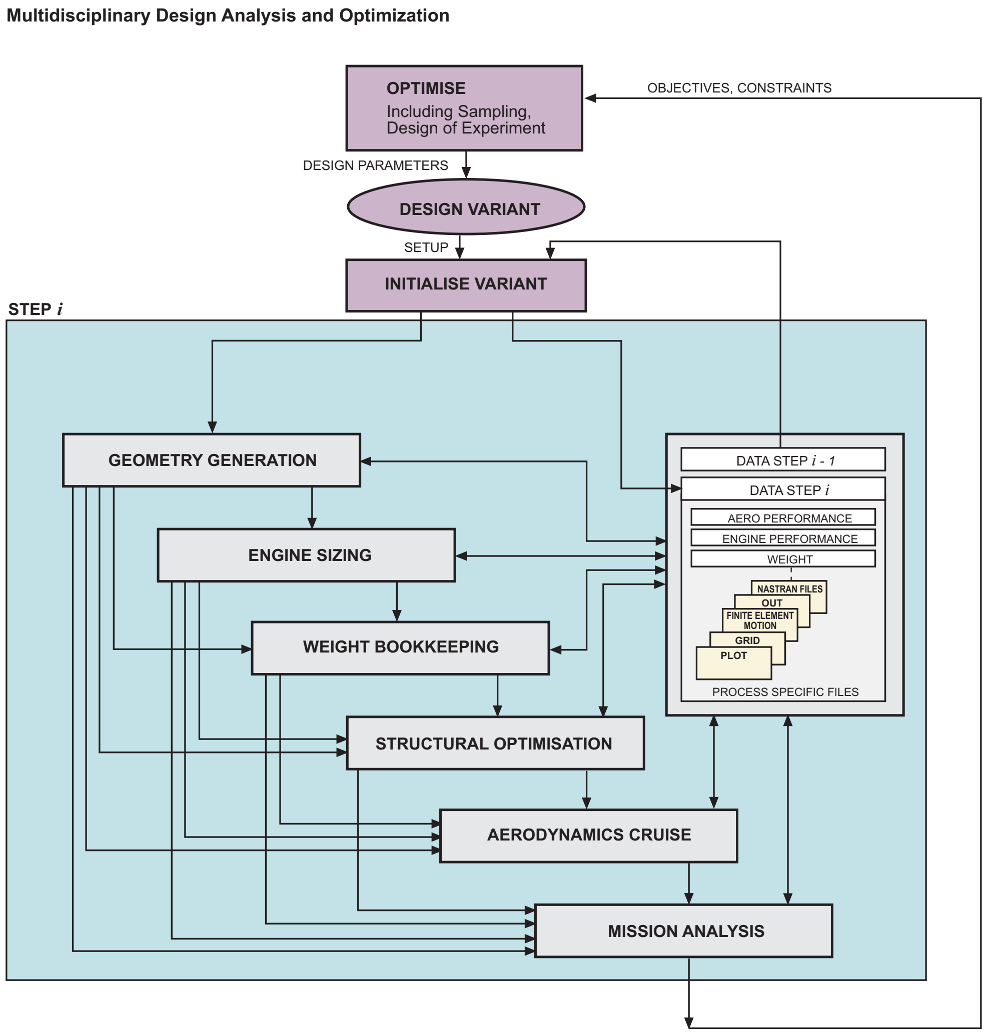
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Multidisciplinary Wing Optimisation



Problem area
In wing design various disciplines are involved. Presently wing design involves a top-level design, which allocates design targets to each discipline. These disciplines perform their designs, using discipline specific methods and tools.

The objective of the described multidisciplinary design optimisation is to base the early wing design on a harmonised set of models and tools.

NLR participates in the large European Union sponsored VIVACE (Value Improvement

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Knowledge area
Collaborative Engineering

Descriptor(s)
MDO,
Collaborative Engineering,
Wing design

through a Virtual Aeronautical Collaborative Enterprise) project, which aims to reduce costs and time-to-market for aircraft and engine design. This paper focuses on the early design of wings.

Description

An automated framework has been realised which couples a number of disciplines tools into an integrated multidisciplinary design analysis system. The realised framework prototype includes

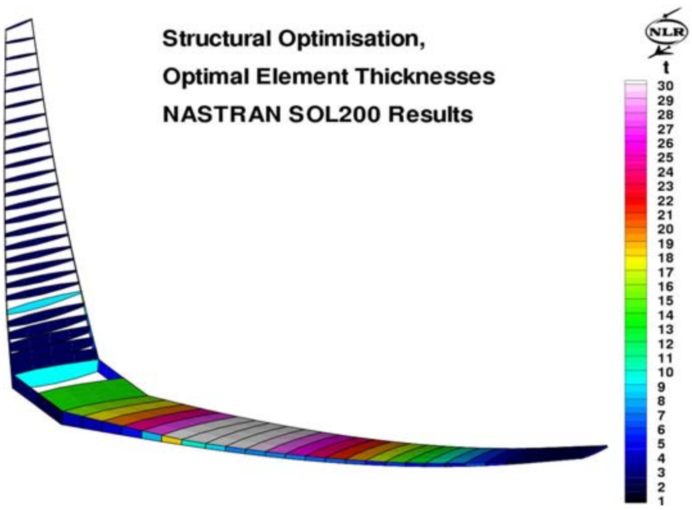
- geometry generation,
- engine sizing, based on a rubberised engine,
- weight bookkeeping
- Finite Element Method based structural optimisation (for a JAR/FAR 25 specified load case),
- high-fidelity CFD based aerodynamic analysis,
- mission analysis.

A first version of this multidisciplinary design analysis framework has been realised.

Conclusion

The development of the multidisciplinary design analysis framework will be continued, taking user feedback into account. Coupling the analysis framework with search and optimisation tools allows for fully automatic exploration of much larger design regions than possible with conventional non-automated methods.

The framework demonstrates NLR's capability to couple and incorporate various existing tools into an integrated design facility. Such integrated analysis and design capabilities can support Dutch industry to move up in the supply chain, i.e. perform more integration activities.



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This report is based on a paper presented at the "Design together, Gain together" forum 2005, Warwick, UK, 20-21 September, 2005.

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Summary

This paper presents multidisciplinary wing optimisation for commercial sub-sonic transport aircraft as an example of NLR's capability to provide a more integrated design facility based on existing tools. Such more integrated design facilities are beneficial for Dutch industry to move upwards in the European design chain.

To define the field, the multidisciplinary design optimisation characteristics are provided. The described wing optimisation work is shown to comply with them, confirming the relevance of this field for wing optimisation. The multidisciplinary wing optimisation is multi-level. The top-level scheme and one lower level, relating to structural optimisation, are provided. The work is performed using the evolutionary approach adopted by the European VIVACE (Value Improvement through a Virtual Aeronautical Collaborative Enterprise) project, with the encouraging results of the first iteration presented.

Acronyms

2D	2-Dimensional
3D	3-Dimensional
AIAA	American Institute of Aeronautics and Astronautics
CFD	Computational Fluid Dynamics
COTS	Commercial-of-the-Shelf
FAR	Federal Aviation Regulation
FEM	Finite Elements Methods
JAR	Joint Aviation Requirements
MDO	Multidisciplinary Design Optimisation
VIVACE	Value Improvement through a Virtual Aeronautical Collaborative Enterprise

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1 Introduction

The Dutch industry is moving upwards in the European aeronautical supply chain. This change increases the demands on the engineering and design capabilities, especially for increased capabilities to judge the effect of changes in a design on the next higher level of the design to allow for an informed design trade-off decision at that higher level. To prepare for such capability, NLR is participating in the European VIVACE (Value Improvement through a Virtual Aeronautical Collaborative Enterprise) [1] project to improve our Multidisciplinary Design Optimisation (MDO) capabilities.

This paper describes the progress made in an integrated multidisciplinary analysis capability for a sub-sonic civil aircraft wing. This analysis capability comprises geometry generation, based on a parameterised aircraft, engine sizing, weight bookkeeping, structural optimisation, aerodynamics cruise and is concluded with a mission analysis. The gained experience can benefit specific industrial work, like a preliminary design study into winglets for the Fokker 100. In more general terms it illustrates NLR's capability to provide a more integrated design facility based on existing tools.

Section two provides some general background information on the forum where this paper has been presented, including a demonstration of the realised capability up to that moment. Next some project context is provided, before proceeding to the multidisciplinary wing optimisation. In the following sections, the concept of Multidisciplinary Design Optimisation (MDO) is briefly elaborated. Subsequently the top-level of the multidisciplinary wing analysis capability is explained, followed by a discussion on a selected single discipline module. This paper ends with the conclusions and current plans for future work.

2 Background

This paper reflects the presentation given at the “Design together gain together” forum 2005. During the presentation a demonstration has been provided of the initial multidisciplinary design optimisation capability as it has been realised at the time of the event. The provided information is complemented with some initial results. This paper concentrates on multidisciplinary wing optimisation. In line with the VIVACE project structure (Figure 1) the requirements for the wing optimisation task have been defined within the sub-project *aircraft* (Figure 1), whereas the technology and solutions for wing optimisation have been realised in the sub-project *advanced capabilities* (Figure 1). The wing optimisation task is not yet directly concerned with the specific requirements that are emerging from the sub-project *engine* (Figure 1).

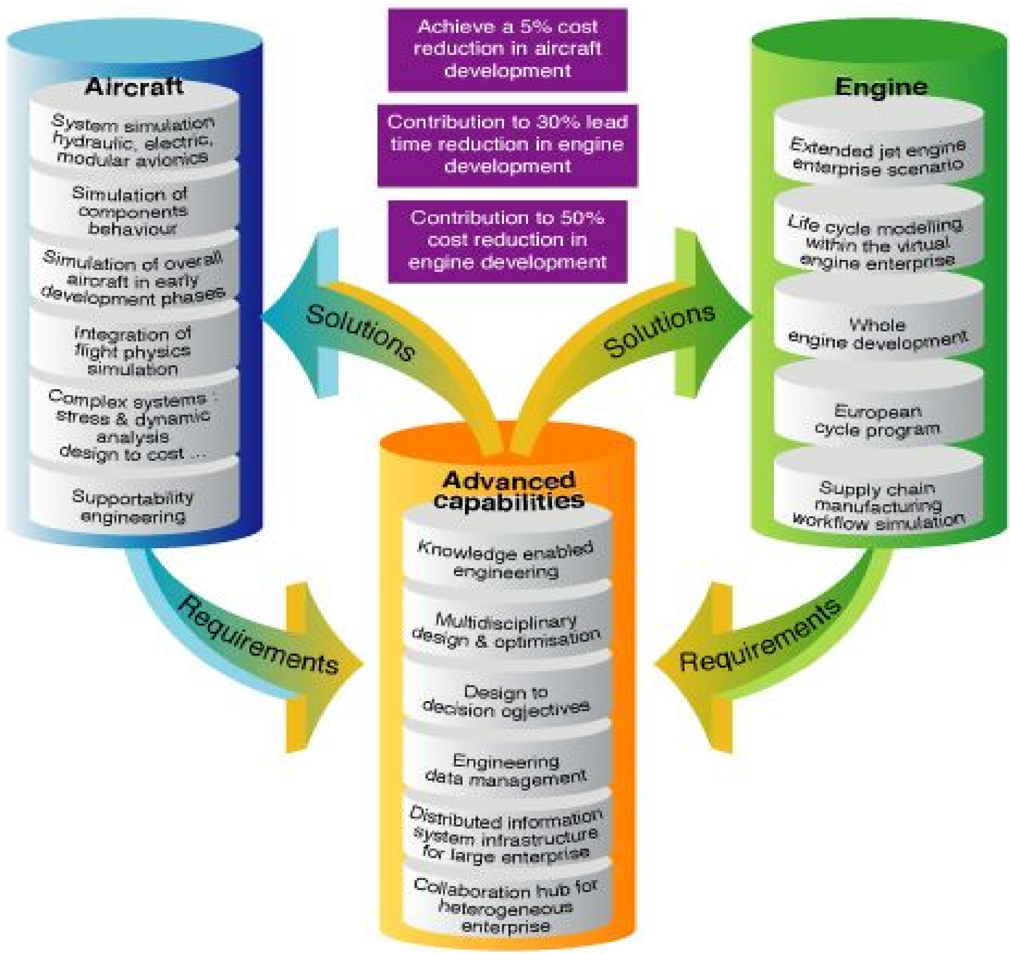

Figure 1 Relations between VIVACE sub-projects, from [1].

VIVACE is a European co-operation having a 4 year duration and nearly 70 partners from 11 countries. VIVACE partners cover the whole spectrum of aeronautics stakeholders ranging from industry via research institutes to universities. The industry is represented by partners selected from the entire supply chain, from integrators to 3rd-tier suppliers. Traditionally such large European co-operations use the classical waterfall development model, a sequential progressing through the system development phases starting with requirements and ending with operation and maintenance. The classical waterfall model is linear, i.e. it does not allow for iterations between phases. A well-known text providing more information on the waterfall model is [2]. Advantages of the waterfall model include that it is well-known and a lot of experience with its application is available, both of which ease management and reduce risk. A disadvantage is that the results become only available at the end of the project, hampering adequate technical guidance during realisation. Another disadvantage is that the standard waterfall development model can not accommodate requirements evolution, which is common in the aircraft development process and consequently encouraged in VIVACE. For the purpose of simultaneous reduction of the time-to-market and reduction of aircraft development costs, as foreseen by the European vision 2020 [3], evolutionary management [4] is a better approach as it focuses on intermediate deliveries which provide user value and which elicit user feedback. VIVACE has adopted such an iterative approach, which is innovative for a European co-operation of this size.

VIVACE has opted for a realisation in three major iterations, as illustrated in Figure 2. Currently the first iteration has been completed. In line with the evolutionary approach, effort is concentrated on the aircraft specific items, i.e. a wing optimisation multidisciplinary analysis capability has been realised. For the optimisation, Commercial-of-the-Shelf (COTS) optimisers can be used, at least for the first iteration. Connecting the various discipline analyses into a combined capability has been accomplished in a straight forward result-oriented way. For future iterations, use of more generic process integration tools, like Fiper [5], are envisaged.

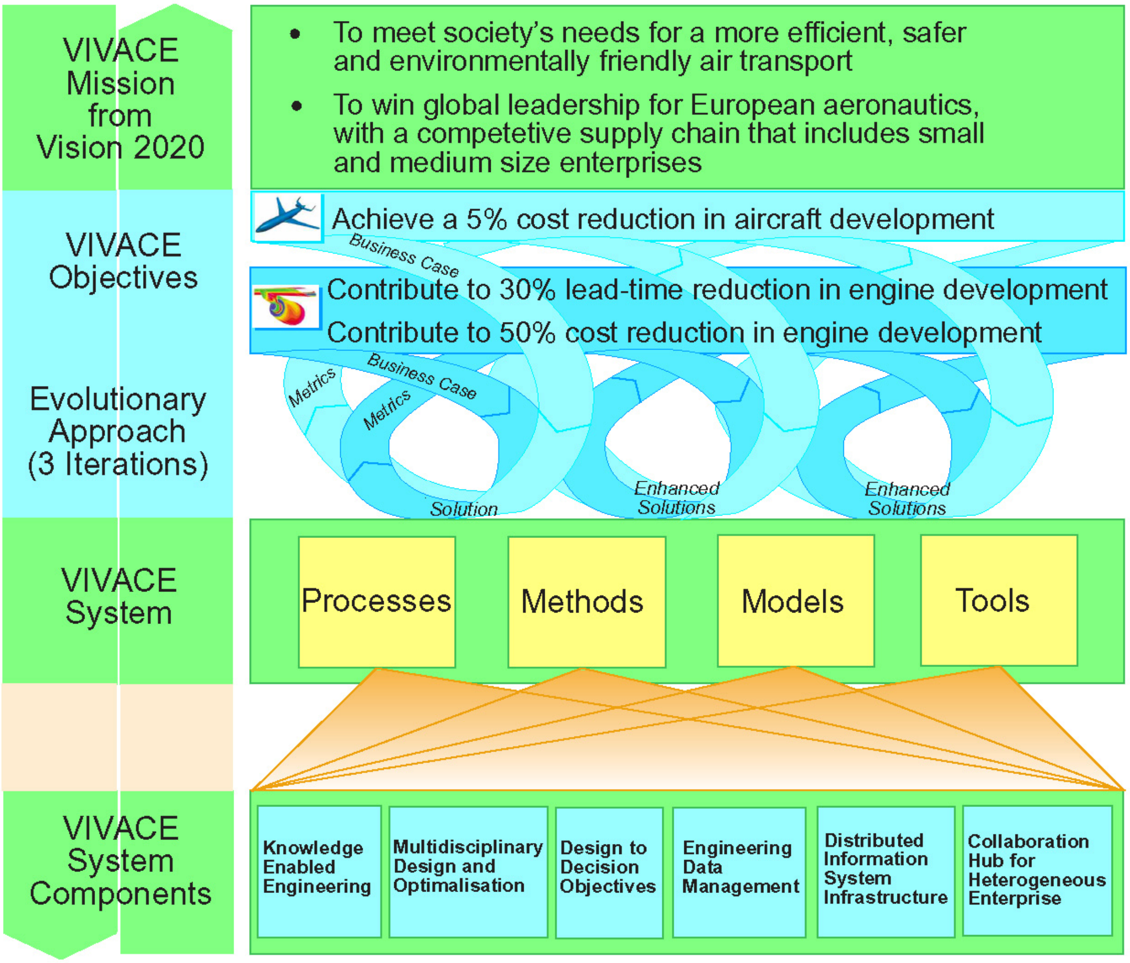

Figure 2 Illustration of the global VIVACE process: the relations between the VIVACE mission, the objectives, evolutionary approach and the system components.

3 Multidisciplinary design optimisation

Wing design is inherently a multidisciplinary activity that includes analyses in disciplines like aerodynamics, structures, flight control, manufacturing, etc. As MDO is not a “fixed format” method various definitions of MDO exist. The American Institute of Aeronautics and Astronautics (AIAA) [6] defines multidisciplinary design and optimisation as a process for the optimal design of complex engineering systems which requires analyses that account for interactions amongst the disciplines (or parts of the system) and which seeks to synergistically exploit these interactions. Their more informal definition is "how to decide what to change, and to what extent to change it, when everything influences everything else." NASA [7] gives a more formal definition of MDO as a methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena. In the AIAA white paper [8] multidisciplinary design and optimisation is characterised as a human-centred environment that:

- allows for the design of complex systems, where conflicting technical and economic requirements must be rationally balanced;
- compresses the design cycle by enabling a concurrent engineering process where all the disciplines are considered early in the design process, while there remains much design freedom and key trade-offs can be effected for an overall system optimum;
- is adaptive as various analysis/simulation capabilities can be inserted as the design progresses and the team of designers tailor their tools to the need of the moment;
- contains a number of generic tools that permit the integration of the various analysis capabilities, together with their sensitivity analyses thereby supporting a number of decision-making problem formulations.

This succinctly describes the NLR’s objectives in VIVACE and in particular those of the Wing MDO team. In general the various disciplines are not necessarily located in the same geographic site or even within the same company, as is reflected in the “CE” (Collaborative Enterprise) of the VIVACE acronym. As this paper deals with work performed during the first iteration, the effects of such multi-company, multi-site collaboration will not be elaborated. More information on these aspects in relation to NLR’s VIVACE contribution can be found in [9] and [10].

Traditionally wing design and optimisation rely on the knowledge and experience of the human designers involved. It is common for a designer to focus on a single discipline. The interaction between the disciplines involved in wing optimisation, for example between aerodynamics and structures, is reflected in the interaction between the human experts. A typical sequence could be the aerodynamics expert designs a wing surface using dedicated computer-based models and tools. The aerodynamics forces are passed to the structures expert who subsequently designs a feasible structure for this wing geometry, using his own dedicated computer-based models and tools. This result can be transferred back to system level and the aerodynamics expert. Due to the human experts involved, a system level iteration typically takes a few weeks to a month to complete. The success of modern aircraft testifies to the effectiveness of this way of working. However the increasing requirements on aircraft performance and consequently on design, as worded as part of the European Vision 2020 [3], justify the investigation of a different, innovative optimisation option. The current work aims to couple the key disciplines involved by integrating the dedicated design tools used. Such an integrated analysis facility, coupled with a suitable optimiser, can explore many designs to find an optimum. The innovation of this work will be to compare the results of such mathematically oriented optimisation with traditional results. Also the current way of working is approaching its limits “to synergistically exploit these multidisciplinary interactions” [5] as more disciplines get involved, e.g. by adding manufacturing concerns and hence costs, or environmental concerns like noise footprint.

For a single wing optimisation exercise, it is expected that the multidisciplinary analysis facility has to be executed hundreds or thousands of times. Consequently there is a strong requirement that the multidisciplinary wing analysis capability is computationally efficient. The analysis methods discussed in the subsequent sections are selected to comply with this requirement.

Please note that fully automatic multidisciplinary analysis and optimisation (i.e. covering all disciplines involved for all relevant design criteria) is not yet considered feasible due to the complexity of the wing design and the many disciplines involved. Various discipline experts remain needed to initiate the optimisation, provide limits for the parameterised design and judge the feasibility of the generated results for the disciplines which are not (yet) taken into account. Automated MDO does provide the opportunity to assess a much larger part of the design space, compared with conventional approaches. This is reflected in the human-centred environment in the AIAA description cited above. Integration of the automated optimisation capability with the human-experts contribution is outside the scope of the current paper.

4 Top-level wing analysis

Figure 3 depicts the top-level view of the wing multidisciplinary analysis capability. The wing optimisation is based on a multi-level optimisation, i.e. in addition to the top-level full-wing analysis and optimisation as shown in Figure 3, some lower-level analyses processes include optimisation processes at their own level. For example the engine-sizing process might optimise the thermodynamic cycles to arrive at minimum fuel consumption. Below some of the major top-level components are briefly described.

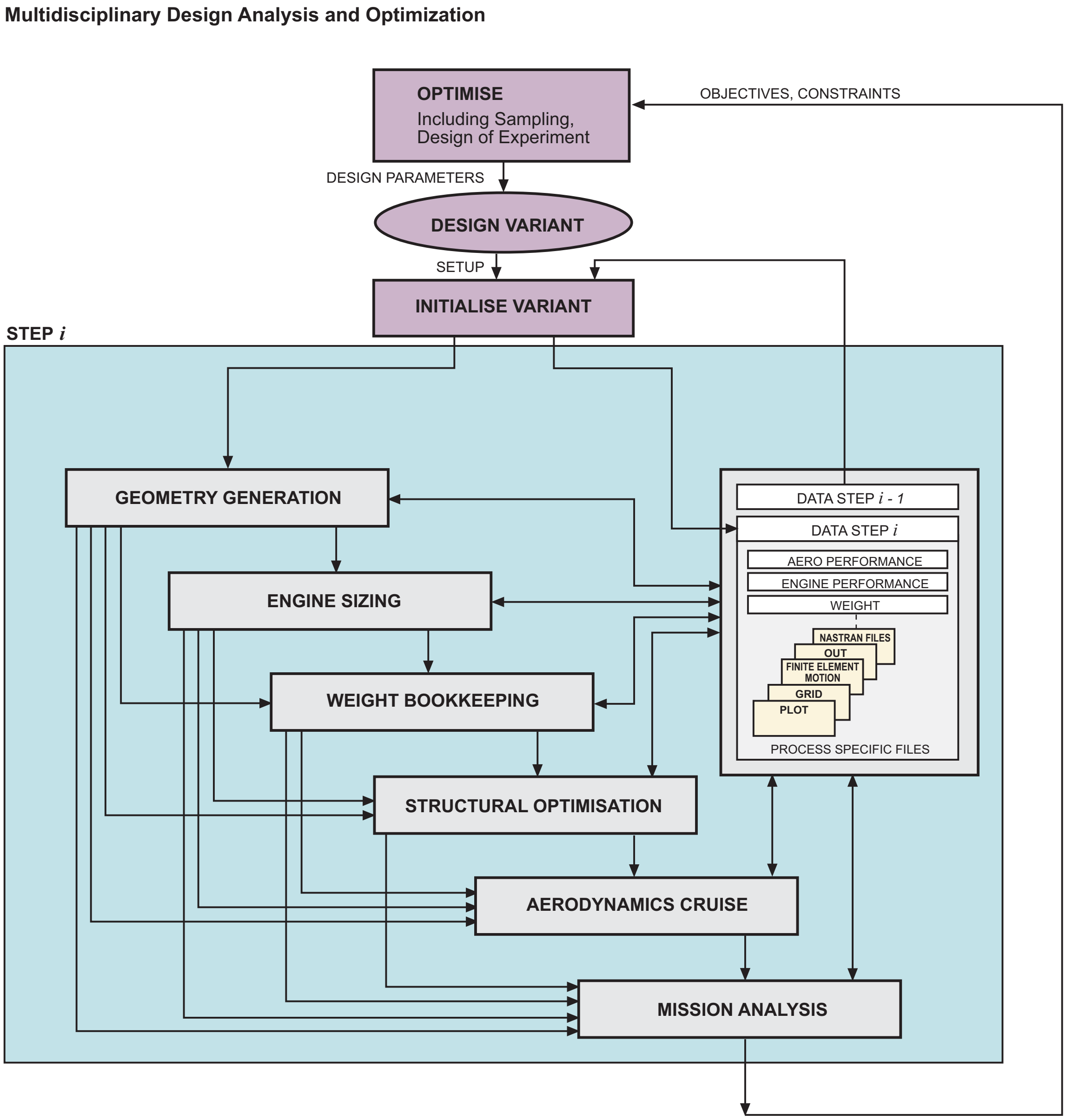

Figure 3 Top-level wing multidisciplinary analysis capability.

The *geometry generation* component (see box in Figure 3) uses a number of parameters to define a wing-geometry. The parameters are depicted in Figure 4. The generated geometry describes the external geometry, for aerodynamic purposes, and the internal geometry defines the internal wing structure, as needed for finite element analyses. In parallel with the work discussed, Cranfield University is working on a more generic version of the geometry generator, which is based on the industry standard CATIA software. Once their geometry generator becomes available it can replace the current geometry generator, illustrating the adaptive characteristic of MDO, as worded by the AIAA definition provided above.

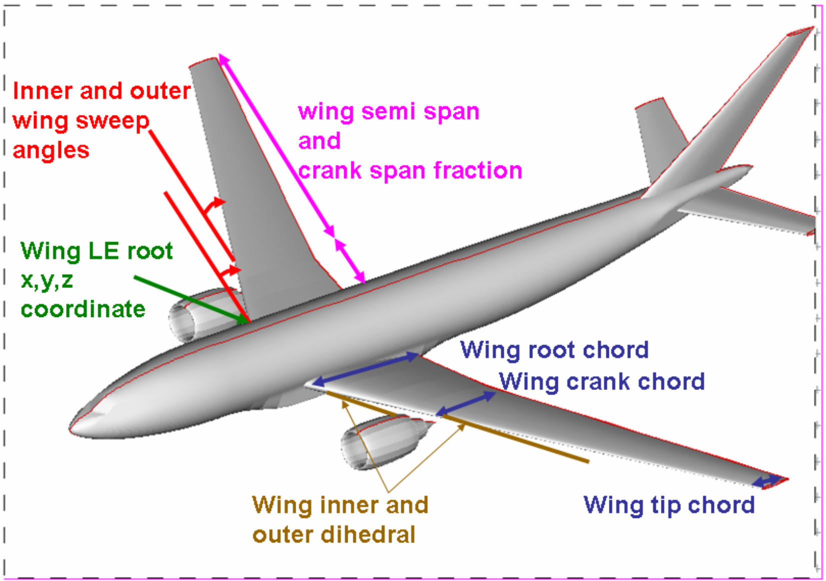

Figure 4 Parameters describing the wing geometry as used for the variant definition.

For *engine sizing* (see box in Figure 3) a scalable engine data set is being used to determine the engine weight and the corresponding fuel flow. From the target range the total fuel weight and fuel volume can be determined. This is also referred to as a "rubberised engine".

The *structural optimisation* component (see box in Figure 3) determines the thickness of the wing's primary structural elements like spars and ribs. For this component, standard desk-top computing equipment allows Finite Elements Methods (FEM) to be used. In the next section this component is explained in more detail.

For the *aerodynamics cruise* component (see box in Figure 3), affordable standard computing equipment allows deployment of NLR's proprietary simulation system MATRICS-V. MATRICS-V performs full-potential boundary layer Computational Fluids Dynamics (CFD) calculation for the aerodynamics cruise component. Future, more advanced, multi-level evolutions of this component could take other relevant flight phases into account.

The last component in Figure 3 is *mission analysis*. This component calculates some key characteristics of the wing design based on the information of the previous components. These characteristics are used by the optimiser to generate the design parameters of the wing variant for the next iteration.

In order to give an impression of the scope of the analyses within these top-level components, as an example the next section elaborates the structural optimisation component.

5 Structural optimisation

The Structural Optimisation component performs the sizing of the wing primary structural elements like spars, ribs and covers, based on certain representative load cases. Ideally, all load cases required to certify the aircraft structure according to the US Federal Aviation Regulation (FAR 25) rules [11] or its European Joint Aviation Requirements (JAR 25) equivalent should be considered. However, in order to simplify the analyses and to comply with the strict computing time demands, as stated in section 4 above, only a single representative load case consisting of a +2.5 *g* pull-up manoeuvre is analysed. Moreover, this load case is configured such that the wing structure experiences maximum bending moments, i.e. maximum payload, full stabilizer trim tank, and full wing tanks.

Figure 5 shows how the structural optimisation is embedded in the multidisciplinary analysis, and how this local-level optimisation loop interacts with the various analysis modules from the other disciplines. An iterative scheme arises as the, a-priori unknown, wing structural weight is fed back via the *total weight* module to the *prelude manoeuvre aerodynamic loads* module where the aerodynamic loads are updated for the new aircraft weight.

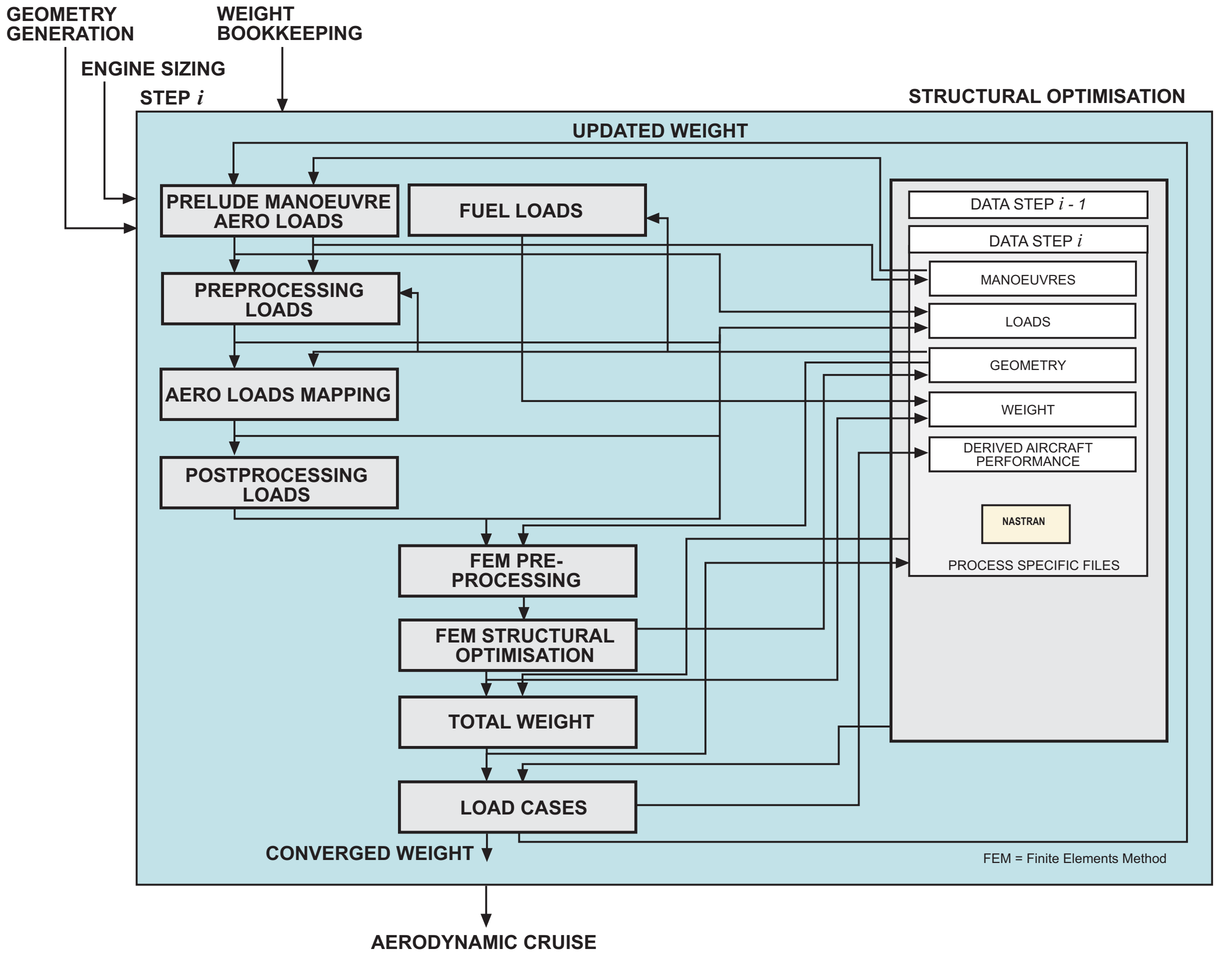

Figure 5 Top-level breakdown of structural optimisation component.

The *prelude manoeuvre aero loads* module (see box in Figure 5) provides the aerodynamic loads by calculation of the flow solution according to an extension of the non-linear lifting line method [12]. This calculation consists of a superposition of aerodynamic forces due to bound/trailing vortices, predicted according to vortex theory, and aerodynamic forces due to viscous effects and shock waves, predicted according to 2-Dimensional (2D) airfoil theory. The aerodynamic loads are translated by the *aerodynamics loads mapping* module into elementary force vectors on the aerodynamic wing surface grid. These force vectors are then mapped, using spline interpolation techniques, to the structural grid points of the aerodynamics/structures interface. The result is a load map representing the external surface pressure loads. The wing geometry as considered in the aero loads calculation, and the resulting aero loads map are illustrated in Figures 6a and 6b below.

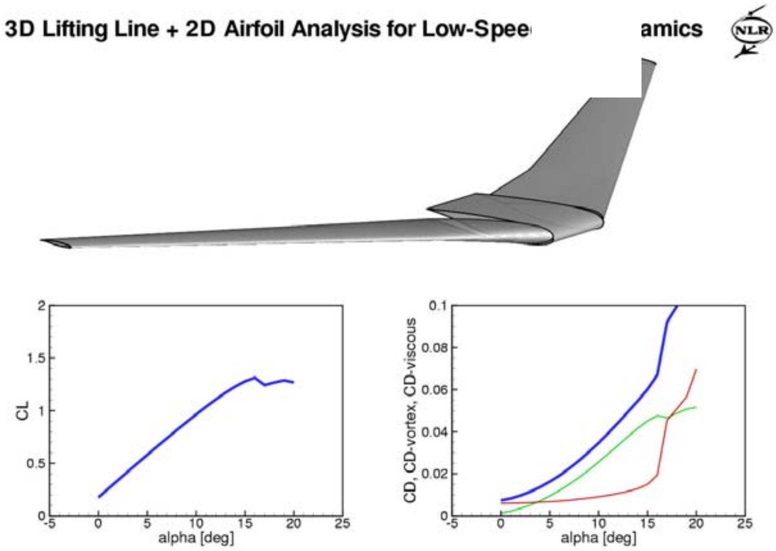

Figure 6a Illustration of the aerodynamic loads calculation considered in the structural optimization process, 3D-wing segments representing wings and fuselage.
Blue represents total drag (CD), green represents CD-vortex and red represents CD-viscous

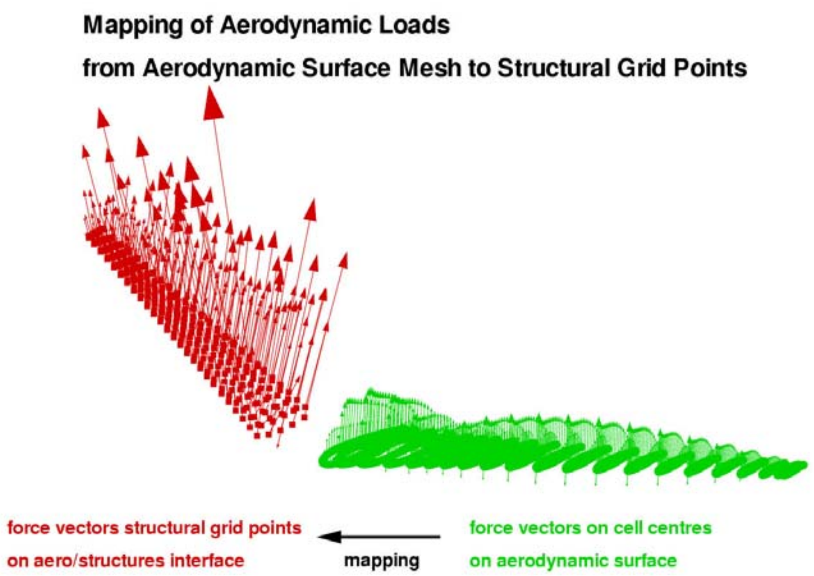

Figure 6b Illustration of the aerodynamic loads calculation considered in the structural optimization process: the mapping of aerodynamic loads (green) to force vectors (red) in structural grid points.

Wing fuel loads during the +2.5 *g* load case are computed as hydrostatic loads on the wing-box lower-skin. In this load case, the various wing tanks are filled to equi-potential levels to reach the maximum take-off weight. The wing structural layout, as provided by the geometry module, is read into a special purpose *FEM-pre-processing* module. This module meshes the structural geometry using quadrilateral elements (covers, spars, ribs) and bar elements (stringers), groups structural elements into design areas and connects the mass items (landing gear and engines) to the primary structure. Next the module reads the externally provided (aerodynamic and fuel) loads and returns a bulk data deck for the subsequent structural analysis step. For the engines, data including weight and thrust forces from the engine-sizing module are used, see Figure 7.

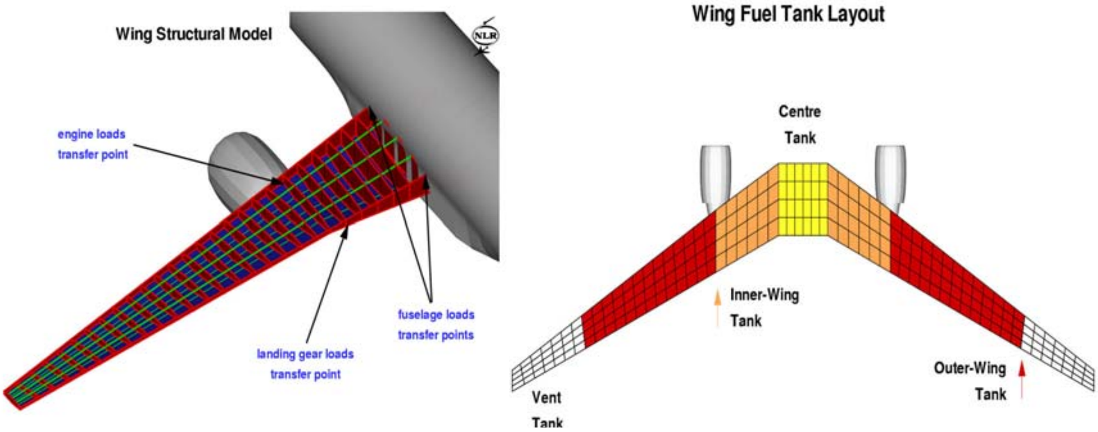

Figure 7 Illustration of the wing structural model, incorporating the loads due to weight and thrust from engines, and fuel weight.

The *FEM structural optimisation* process (see box in Figure 5) is illustrated in some more detail below in Figure 8.

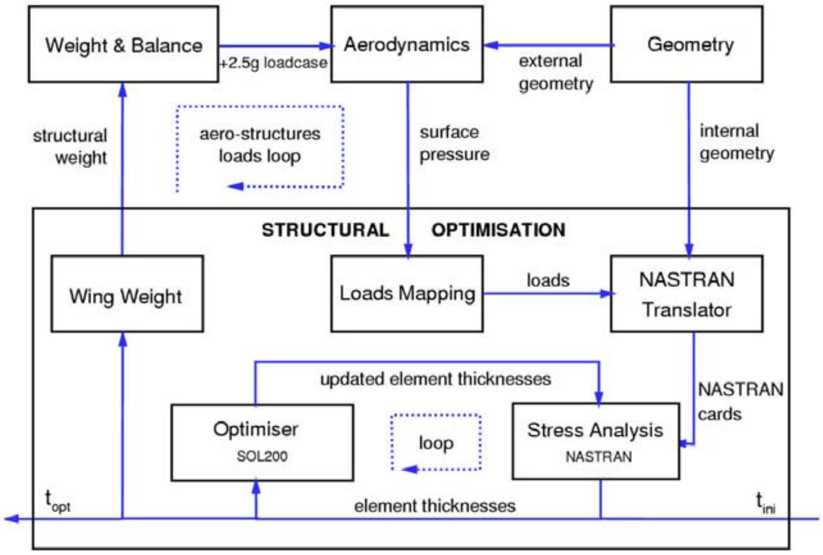

Figure 8 Detailed representation of the structural analysis and optimisation process.

The structural analysis is based on the finite element method implemented in MSC-NASTRAN. The response of the structure (local stresses and strains) to the applied loads (aerodynamic, weights, thrust) is evaluated by NASTRAN’s linear static analysis of the wing. For the sub-sonic aircraft wing as shown in Figures 9-13 this involves 748 elements and 1800 degrees of freedom. The optimisation is performed using NASTRAN's gradient based SOL200 optimiser, which directly controls the linear static FEM analysis. The optimisation problem considered is a constrained minimisation of the structural weight of the wing:

$$\min_{x_i} f(x_i)$$

$$\textit{subject to: } g_j(x_i) = \sigma_j(x_i) - \sigma_{\max} \le 0 \quad \forall i, j \quad ; \quad l \le x_i \quad \forall i$$

Here the objective function f represents the wing's structural weight, which depends on the design parameters x_i (plate thicknesses of spars, ribs and covers, defined for each design area i). The wing structural weight is minimised by variation of these design parameters that are bound by a minimum value l, for which a value of 2 mm is chosen. Furthermore the optimisation is constrained by the non-linear function g_j, which represents the local value of the Von Mises stress σ_j in each of the FEM element centres j and which is bound to σ_{max}, the maximum level of 200 N/mm^2 (isotropic aluminium). The Von Mises stresses in the constraint function g result from the linear static structural analysis of the wing for the *+2.5 g* manoeuvre concerned. The optimisation analysis converges in approximately 20 iterations. Some of the results of the optimised wing structure are given in Figures 9-13 below.

Figure 9 Von Mises stresses for wing internal structures at +2.5 g manoeuvre

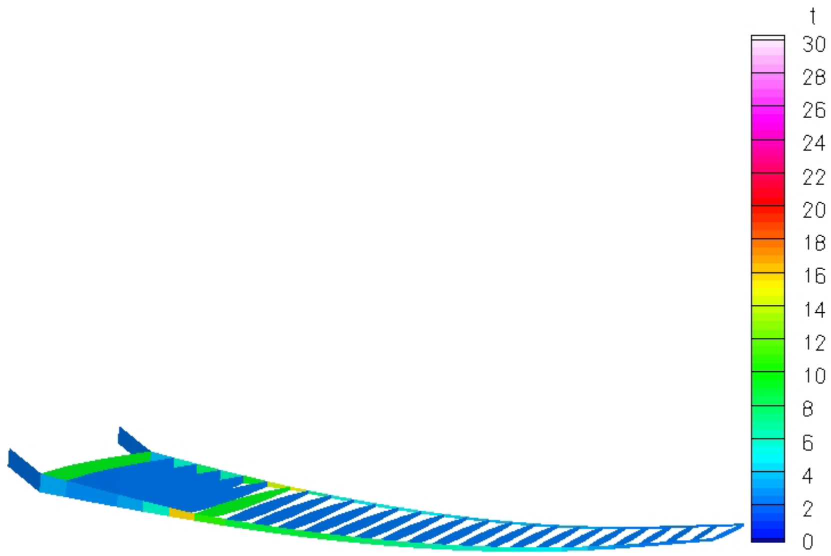

Figure 10 Wing internal structures thickness optimisation at +2.5 g manoeuvre

The thicker rib in the inner wing (and the adjacent beam sections) is where the engine weight and thrust are transferred, see also Figure 7. Towards the wing tip all ribs have the minimum thickness whereas the maximum Von Mises stress is not reached (Figure 9). This indicates that, for the outer wing, the wing design does not utilise the full capabilities of the used material for the +2.5 *g* manoeuvre analysed.

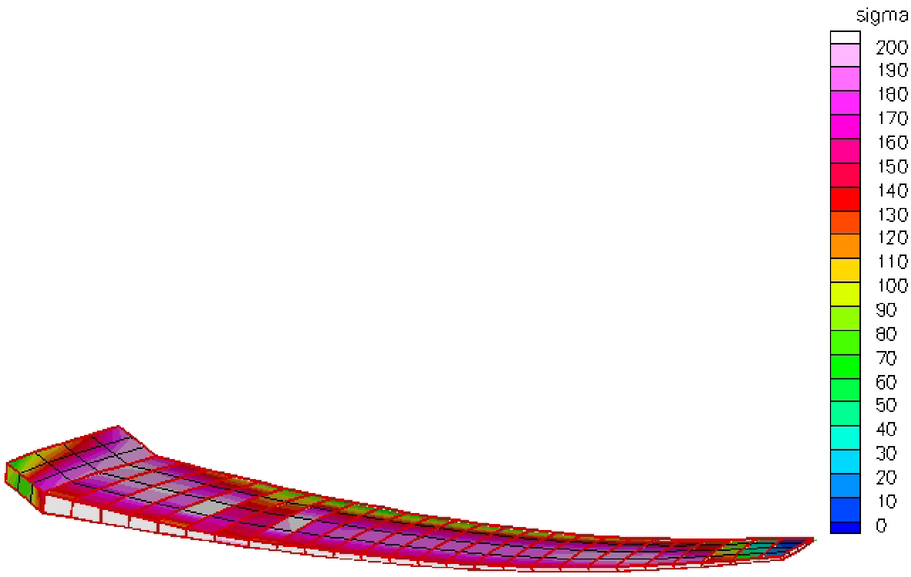

Figure 11 Von Mises stresses for wing skin at +2.5 g manoeuvre

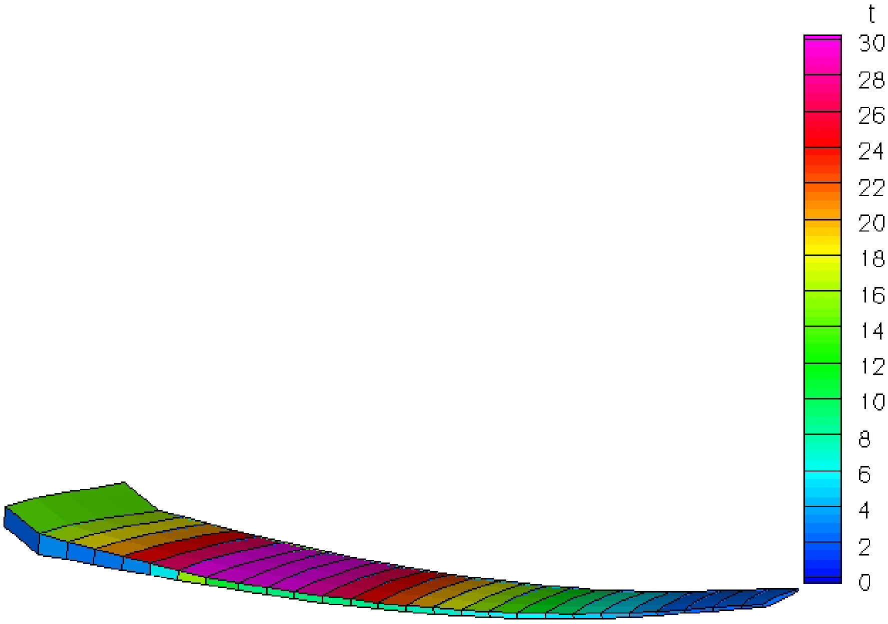

Figure 12 Wing skin thickness optimisation at +2.5 g manoeuvre

Only the outermost design areas experience a Von Mises stress below the maximum, see Figure 11. Figure 12 shows that for these design areas the wing skin reaches the minimum level

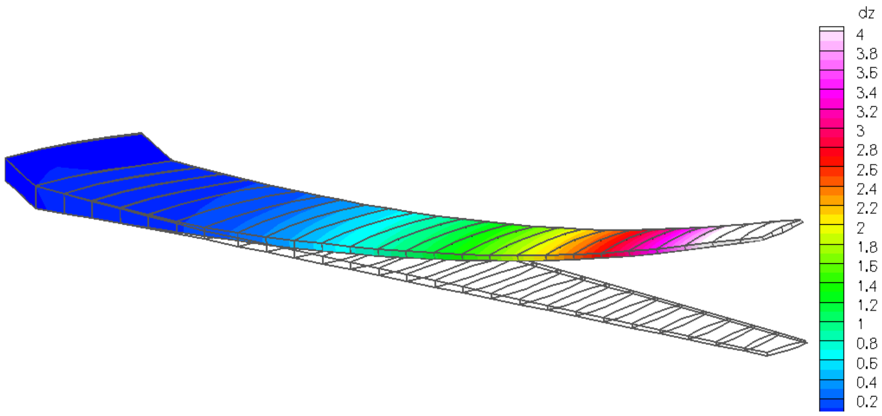

Figure 13 Maximum wing deformation (in meters) at +2.5 g manoeuvre

Figure 13 depicts the significant wing deformation for the +2.5 *g* manoeuvre. It should be noted that this local level structural optimisation involves only the structural elements' thicknesses. Incorporation of also the wing planform design parameters in this structural optimisation, i.e. aero elastic tailoring, is achieved via the higher level optimisation loop but is currently not specifically considered.

Figures 9-13 illustrate the obtained material thickness distribution of the wing covers and wing ribs, as well as their resulting von Mises stresses and the resulting deformation of the optimised wing. The finite element analysis does not yet include details of the structure which arise from manufacturability or maintainability constraints. Due to the modular approach of the design capability, modules addressing such items can be either included in the lower-level loop of Figure 5, or in case the interaction is considered less direct in the top-level loop of Figure 3. Several studies suggest a factor of 1.5 between the FEM-optimised structural weight and the actual real-life aircraft structural weight. This additional 50 percent is designated as "secondary" structural items and included in the weight breakdown. Again, as more disciplines are included in the analysis capability, actual data could replace such significant additional engineering weight factors and take them into account when optimising.

During the *global-level* wing planform optimisation (Figure 3), subsequent aircraft variants inherit their initial material thickness distribution from the baseline aircraft. These material thicknesses are adapted to the +2.5 *g* manoeuvre loads in the structural optimisation loop, and then updated in the global level wing data base. After this update the manoeuvre loads can be recalculated and the structural optimisation can be run again taking these updated loads into account. With each such pass through the structural optimisation loop of Figure 5, the wing weight is observed converging about one order of magnitude. Initial experiments indicate that executing a sequence of two structural optimisation loops was found to provide sufficiently well converged wing weight data.

6 Conclusion and future work

This work addresses all four AIAA multidisciplinary design optimisation characteristics mentioned above. Clearly the optimisation has to balance conflicting technical and economic requirements, demonstrating the first AIAA MDO characteristic. By integrating various design disciplines into one facility, the design cycle is compressed, illustrating the second AIAA MDO characteristic. The facility is adaptive as more discipline modules can be added or existing ones can be removed (or expanded) tailoring the tool suite to the design task, as stated in the third characteristic. Especially for the collaboration aspects, generic tools can, and indeed are planned, to be deployed, as worded in the last characteristic.
The current status of the multidisciplinary wing optimisation is integrating some main disciplines into a single tool suite. Once this activity is completed, the first optimisations will be performed. The experience up-to-date is that the models used for the various disciplines have computational requirements that are compatible with the requirement of the wing MDO, i.e. allow a sufficient part of the design space to be covered as needed by the automatic optimisation proposed.

Based on the experience with those first optimisations the next steps will be defined, which is compliant with the evolutionary approach, and which is an improvement of the waterfall approach as typically used in previous large European collaborations.

Acknowledgement

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