A98-31694

ICAS-98-6,8,2

FROM A MONO-DISCIPLINARY TO A MULTI-DISCIPLINARY APPROACH IN AEROSPACE: AS SEEN FROM INFORMATION AND COMMUNICATION TECHNOLOGY PERSPECTIVE

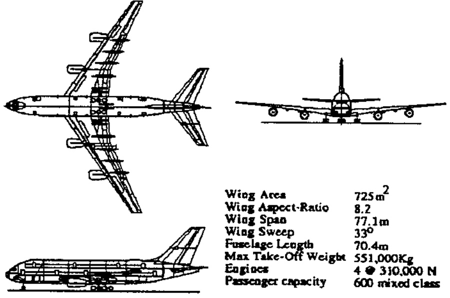
M.E.S. Vogels, P. Arendsen, R.J. Krol, M. Laban, G.W. Pruis,
National Aerospace Laboratory NLR, P.O. Box 90502, 1006 BM Amsterdam, The Netherlands,
tel: +31-20-5113-426, fax: +31-20-5113-210, e-mail: vogels@nlr.nl

Abstract

In Europe, the MDO Consortium has validated the viability of Multi-Disciplinary Optimisation (MDO) for simplified but realistic aircraft preliminary design tasks concerning the design of a large civil a/c where a non-trivial interaction is expected between the mono-disciplines of aerodynamics and structures. NLR, one of the Consortium members, has carried out the work in a multi-disciplinary team with specialists from aerodynamics, structures, and information and communication technology (ICT). Whereas the team takes responsibility for the harmonisation and coherence of the multi-discipline research, each discipline is responsible for the own discipline's contribution. In particular, the ICT discipline is responsible for the coherence of the activities on ICT level. The most relevant requirements on ICT in a transition from a mono-discipline approach to a multi-discipline approach, as we experienced them, are presented, along with our solutions, and the results for a wing shape optimisation study with simultaneous influence from the aerodynamic and the structures area.

Introduction

To effectively resolve cross-discipline trade-offs both to improve aircraft performance and reduce development time scales and costs, concurrent engineering principles are under investigation for the preliminary design stage. In Europe, the MDO Consortium [1] is addressing integration of design and analysis tools creating a Multi-Disciplinary Optimisation (MDO) capability (Refs. [mdo-96], [Allwright-96a]). One of the purposes is to validate the viability of MDO for simplified but realistic aircraft preliminary design tasks concerning the design of a large civil a/c where a non-trivial interaction is expected between the mono-disciplines of aerodynamics and structures. The a/c is shown in Figure 1. The purpose is NOT to find a good design, but to understand the issues for employing multi-discipline optimisation.



Wing Area	725 m^2
Wing Aspect-Ratio	8.2
Wing Span	77.1m
Wing Sweep	33°
Fuselage Length	70.4m
Max Take-Off Weight	551,000Kg
Engines	4 @ 310,000 N
Passenger capacity	600 mixed class

Figure 1 MDO Reference Aircraft

NLR, one of the Consortium members, carries out the work in a multi-disciplinary team with specialists from aerodynamics, structures, and information technology. Whereas the team takes responsibility for the harmonisation and coherence of the multi-discipline research, each discipline is responsible for the own discipline's contribution. In particular, the ICT discipline is responsible for the coherence of the activities on ICT level.

The requirements on ICT have been identified and prioritised in accordance with ongoing optimisation work. This means that the ICT mechanisms were developed concurrently with the ongoing optimisation work.

In the next sections, the ICT mechanisms are presented, along with the results for a wing shape optimisation study.

---

[1] The MDO project (Multi-Disciplinary Design, Analysis and Optimisation of Aerospace Vehicles) is a collaboration between British Aerospace, Aerospatiale, DASA, Dassault, SAAB, CASA, Alenia, Aermacchi, HAI, NLR, DERA, ONERA, and the Universities of Delft and Cranfield. The project is managed by the British Aerospace and is funded by the CEC under the BRITE-EURAM initiative (Project Ref: BE95-2056).

21st ICAS Congress
13-18 September 1998
Melbourne, Australia

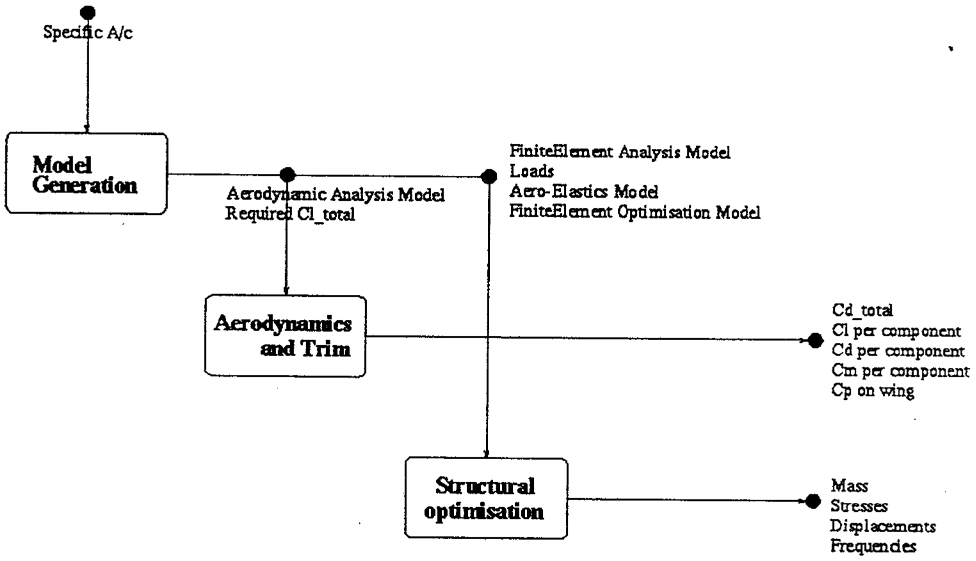


Figure 2 Multi-Discipline Analysis

The transition

In our work, the most relevant requirements on ICT in a transition from a sequential mono-discipline approach to a multi-discipline approach proved to be:

- to capture the multi-discipline process,
- to decrease the dependency on the availability of all members of the MDO team, and
- to provide a variety of control structures over calculations.

The mechanisms are described below.

Capturing the MDO-process In general, interpretation of results requires knowledge of the process in which the results were generated. In Multi-Discipline Optimisation, where the process changes frequently, the capturing of the process is essential. An excellent technique for describing the contributing disciplines and their interactions are so-called N^2 diagrams as in Figure 2. The diagram shows that our multi-discipline analysis consists of the activities "Model Generation", "Aerodynamics and Trim", and "Structural Optimisation". The activities "Aerodynamics and Trim", and "Structural Optimisation" can be executed in parallel since the loads for the "Structural Optimisation" are calculated during the "Model Generation". A detailed description of the technique and the way it has been used in the MDO project is given in [Vogels-98].

Reducing the dependency on individual team members. Whereas in mono-disciplinary work it may be acceptable that the work halts when a specialist is unavailable, in multi-disciplinary work carried out in a team, it is not acceptable. The work may have to be taken over by a colleague less familiar with the MDO problem, or by a multi-discipline team member of a different discipline.
When trying to perform the absent specialist's work, the colleague may have to find out:

- where to find and how to obtain access to the specialist's mono-discipline software and data
- how to construct or to find necessary input for the software and where to store the output
- on which computer in the network to run a specific program with stumbling blocks authentication, accounting, and special commands such as "telnet" for log-in to remote systems and "rsh" for starting a program on a remote machine as if it were on the local machine.
- how to transfer files between computers, or store and organise data on particular file systems shared between the computers involved.

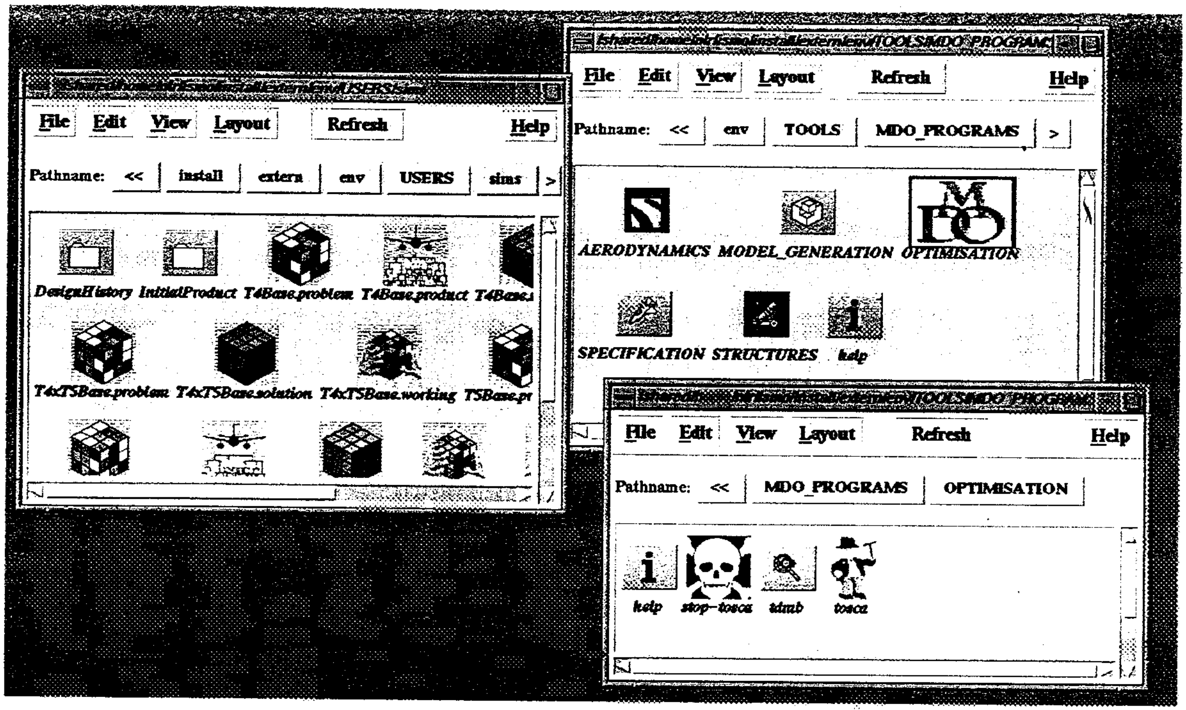


Figure 3 View on Multi-Discipline Analysis, Design, and Optimisation Framework, based on SPINE

For this purpose, all multi-discipline information (t.i. software, data and reports) on the heterogeneous computer network is integrated within an MDO enviroment. The system integration is performed with SPINE (see [Baalbergen-98]). In the MDO environment, the above mentioned problems are addressed by:

- making the mono-discipline software and data available to all the team members. In Figure 3, an example of the organisation of software and data within the MDO environment is shown. Software and data are displayed as icons. Aggregates of data and software are represented by icons as well. For instance, in the upper right-hand side window the icon labelled “MODEL_GENERATION” represents the set of all model generation tools. With these tools, the activity “Model Generation” in the N^2 diagram in Figure 2 can be executed.
- providing on-line help for using the software. For example, in Figure 3 help information is available for each of the tool-boxes in the upper right-hand side window, such as “AERODYNAMICS”, as well as for each of the programs in the lower right-hand side window, e.g. “tdmb” (for product modelling and browsing [Allwright-96b]) and “tosca” (for optimisation driver [Sims-98]). The help-information is displayed when a user selects a toolbox or a program, and drops it on the help icon.
- hiding the details concerning the network, remote execution of programs, and file transfers between computers from the user.

In our work at the MDO-project, we experienced the use of the MDO environment based on SPINE to be useful in reducing the dependency on individual team members.

Enabling various control structures At various stages of the MDO-activity, different types of control over the calculations in the MDO environment are required. Four types of control are distinguished:

- Single tool type. During the first optimisation iteration(s), each program shall be executed individually, to allow for detailed inspection of results and adjusting configuration parameters and input data. At this stage, a high level of flexibility is required and is more important than reducing the problem turn-around time

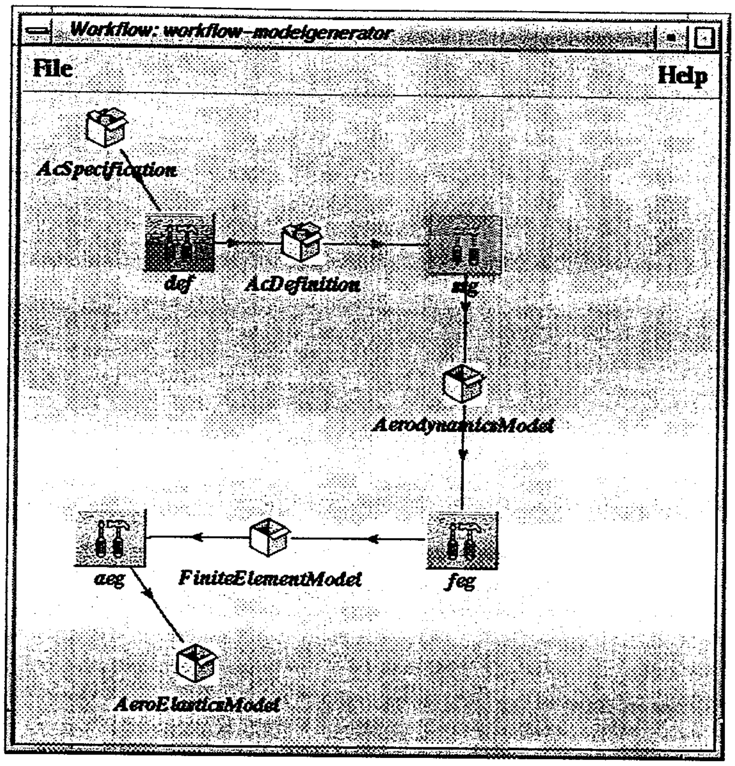


Figure 4 Example of a workflow for ModelGeneration using SPINE (the program ssg is executing)

Performing all steps in an optimisation cycle requires relatively many operations.

- Single Discipline type. In the next stage, when the single applications are tuned to the problem, starting each of the applications by hand tends to become annoying. A lower level of flexibility is required, reducing the number of operations in a single discipline becomes more important. Reducing the number of operations can be achieved by chaining of tools. There are two approaches to solve this problem. The tools can be chained using the workflow editor, which is part of SPINE (see Figure 4). The workflow can now be run instead of the individual tools. Another approach is to integrate the tools as one (new) compound tool in the environment.
- Design point type: Applications and chains of applications are executed for a set of design points. Another way of reducing the number of operations, lies in the fact that the various disciplinary calculations are performed for a set of design points. Instead of executing an application or a chain of applications for each design points individually, it can be started for all design points with one operation. This requires a way to specify the set of design points and a structured file organisation from which the design points can be mapped to the proper input files.
- Iteration type: A complete multi-disciplinary optimisation iteration is captured by one button, the optimisation solution control agent "tosca" (see [Sims-98]). The multi-disciplinary process is now being captured by operations that are in number independent of the number of design points and the number of applications within the various disciplines. To abstract from the different disciplines to the level of multi-disciplinary optimisation, all single discipline compound tools may be chained in a workflow, in the way they are called for the complete set of design points. When the tools that are used for distributing data to the single disciplines and for combining the single discipline results are added to the workflow, a complete multi-disciplinary optimisation cycle can be performed by pressing a single button.

The wing shape design study

Within the MDO-project, Task 5 "Surface Shape Optimisation", a wing shape design study has been performed. The objectives were to demonstrate a civil aircraft wing design procedure taking wing weight and overall configuration drag into account. The wing design methodology was based on applying thickness, twist, and wing aerofoil shape perturbations, and computing wing weight and drag sensitivities with a finite difference technique. Wing weight and drag penalties were combined in one objective function "direct operating cost" (*DOC*) which was minimised by an optimisation algorithm. Not only the design itself but also the multi-disciplinary design system itself is of interest here. The multidisciplinary design system is demonstrated using the MDO reference aircraft as point of departure. The actual design process consists of two steps. In a first step, the span wise wing thickness and twist distributions are optimised for fixed aerofoil shapes. In a follow up, the wing thickness and twist distributions are combined with the aerofoil shape perturbation functions to demonstrate a complete wing shape optimisation for a given planform.

Objective Function and Analyses Tools. The following objective function is adopted to link wing weight and drag penalties:

$$\Delta DOC = \Delta W \text{ (tonnes)} + \Delta Cd \text{ (counts)} \qquad (1)$$

where ΔW is the change in structural weight of one half-wing torsion box expressed in tonnes and ΔCd is the change in total (stabiliser-trimmed) aircraft drag coefficient expressed in counts.

The drag coefficient is computed by NLR's full potential flow coupled boundary layer code MATRICS-V [van Muijden-94]. The flow solver system features an automated single block grid generator which is interfaced with the MDO surface shape generator. Angle-of-attack and stabiliser lift are adjusted during the iterative flow solution process such that the required overall configuration lift coefficient is achieved under the constraint of zero pitching moment.

Wing structural weight, ΔW, is computed by optimising the wing skin thickness distribution, stiffeners, and spars using NLR's structural optimisation code B2000 such that it meets the material stress constraints in the several flight conditions. It implies a sizing optimisation with 155 design variables and tens of thousands stress constraints on this structural level.

Optimisation Strategy and Sensitivity Computation. An optimisation algorithm is used which requires the current value of the objective function ΔDOC and its derivatives with respect to the design parameters. The optimiser stores the optimisation path in memory and uses this information to compute approximated second order derivative information. The second order derivative information may be used to expedite optimiser convergence near the minimum of the objective function. The update method used is the well-known BFGS-method ("Broydon-Fletcher-Goldfarb-Shanno"). A finite difference technique is adopted to compute the required objective function derivatives numerically.

Aerofoil Shape Perturbation Function Definition. The design process is based on perturbing aerofoil shapes under control of an optimiser. This requires a parametric description of the aerofoil shape perturbations. NLR has chosen a square root stretched n-th order Bernstein polynomials as base functions for the shape perturbations.

In the first part of the design process, the wing spanwise thickness and twist distributions are optimised while keeping the wing aerofoil shapes fixed. The thickness distribution is governed by linear interpolations of the thickness at root, crank and tip, while the twist distribution is expressed in linear extrapolated terms of twist of crank and tip. This part concerns the designs 0 to 5.

The second part of the design includes aerofoil shape optimisation besides the wing spanwise thickness and twist distribution optimisation. This implies that the set of 5 variables is extended with 12 variables governing the airfoil shape. These 12 variables are 3 Bernstein polynomial base function scale factors at root/tip and lower/upper side. Inboard, crank, and outboard wing station aerofoil shape perturbation parameters are obtained through linear interpolations from the root and tip stations. This part concerns designs 6 to 8.

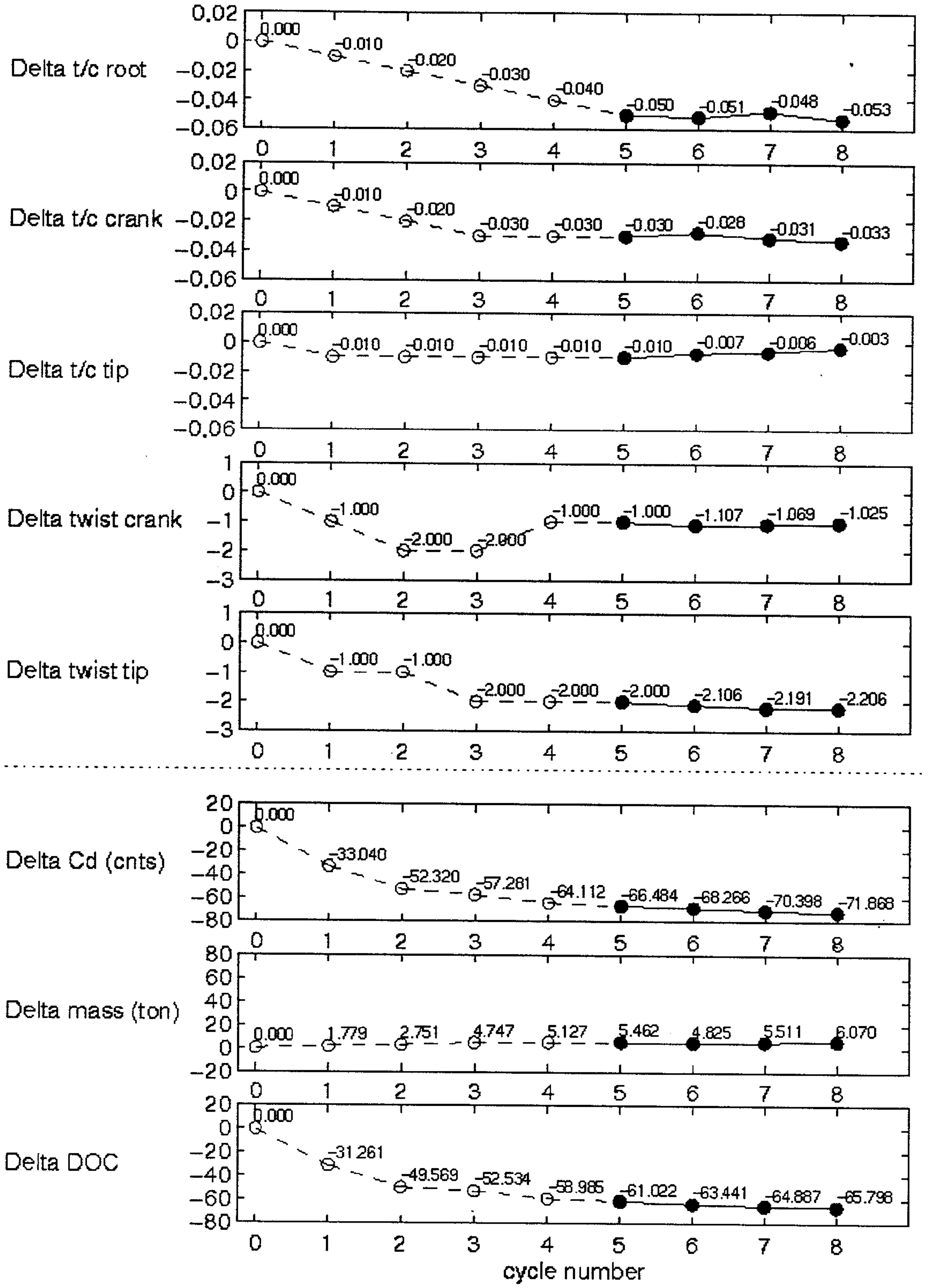


Figure 5 Design history for 5 of the design variables, the drag, the wing weight, and the objective function

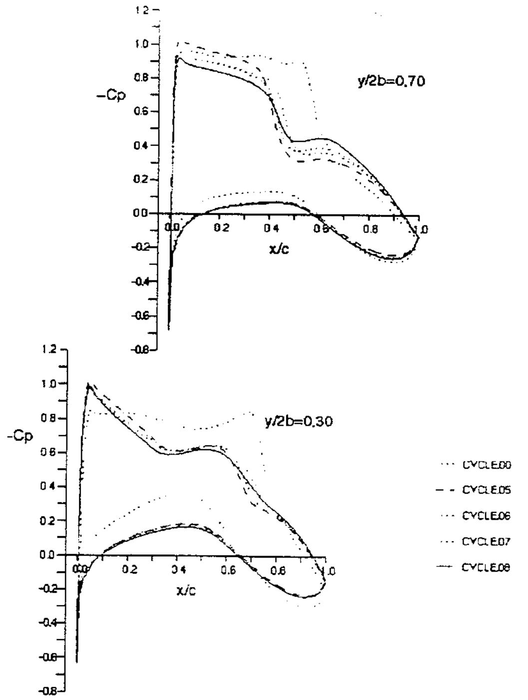


Figure 6 Evolution of the wing pressure distribution during the optimisation process.

Results. The trajectory in the design space for the first 5 of the 17 design variables and the resulting drag coefficient, wing weight, and objective function are shown in Figure 5. In five cycles, the objective function (starting at 0) reaches a minimum of -61 with ΔCd=-66 counts and ΔW= +5 tonnes. The three additional design cycles bring the objective function down to -66 with ΔCd=-72 counts and ΔW= +6 tonnes.

The optimisation process results in a wing with a relatively thin root section

t/c=14.5%-5.0%=9.5%

and a relatively thin crank section

t/c=10.0%-3.0%=7.0%

when compared to the MDO reference aircraft (Figure 1). The thin root section originates from a strong aerodynamic drive to reduce wave drag in combination with (suspected unrealistic) almost zero wing weight sensitivity to root thickness perturbations. One would expect a decrease in structural wing weight with increasing (root) thickness since, in general, a thicker structure is more efficient when loaded in bending and torsion. A thicker structure however also implies larger ribs, which are not included in the current structural optimisation process and therefore unrealistically heavy. An additional effect is the increase in structural loading with increasing thickness due to a decrease of inertia relief. These effects apparently add up to an almost zero root thickness mass sensitivity in our results.

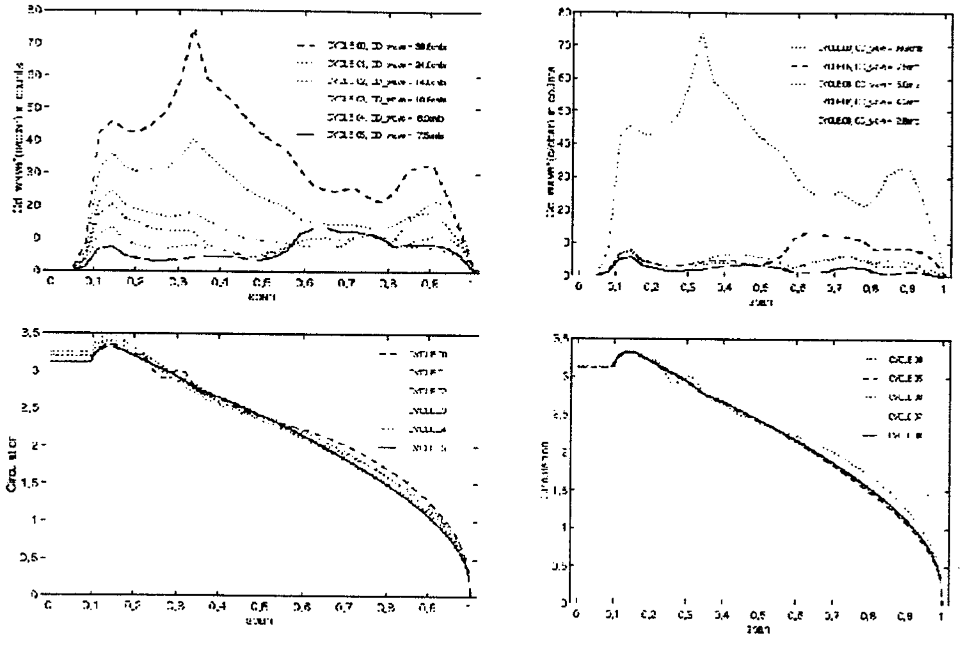
In the final 3 cycles the wing thickness and twist distributions do not change significantly, except perhaps a wing tip thickness gain of almost 1 %.

The evolution of the wing pressure distribution during the optimisation process is shown in Figure 6. At the inboard wing (at y/2b=0.30), the pressure coefficient immediately preceding the shock wave on the upper surface is considerably lower for the optimised wing while the nose suction peak is considerably higher.

At the outboard wing (at y/2b=0.70), the main observation is a forward movement of the shock wave. In the final 3 cycles the shock wave is disappearing on the inner wing and reduces significantly on the outer wing. The increasing outboard wing section rear loading balances the lift losses due to the lower pressure coefficient in front of the shock wave on the wing upper surface.

The evolution of the spanwise wave drag and circulation distribution during the optimisation process is shown in Figure 7. At design 5, the Cd_wave is 7.5 counts versus 39.6 counts for the MDO reference wing. Circulation on the outboard wing reduces during the design process while this is not compensated at the inboard wing. Wing lift reduces as a result of a reduction in stabiliser tail down force required for momentum equilibrium (Reference aircraft: -0.031, optimised aircraft -0.016) under the constraint of constant overall configuration lift. The final 3 cycles show a further reduction of wave drag to 2.5 counts in design 8. Most wave drag savings occur on the outboard wing despite a small increase in the local sectional loading and thickness. Therefore, this effect must be attributed to the (tip) aerofoil shape optimisation. Apparently, the optimisation process is aiming for a uniform wave drag distribution in span.

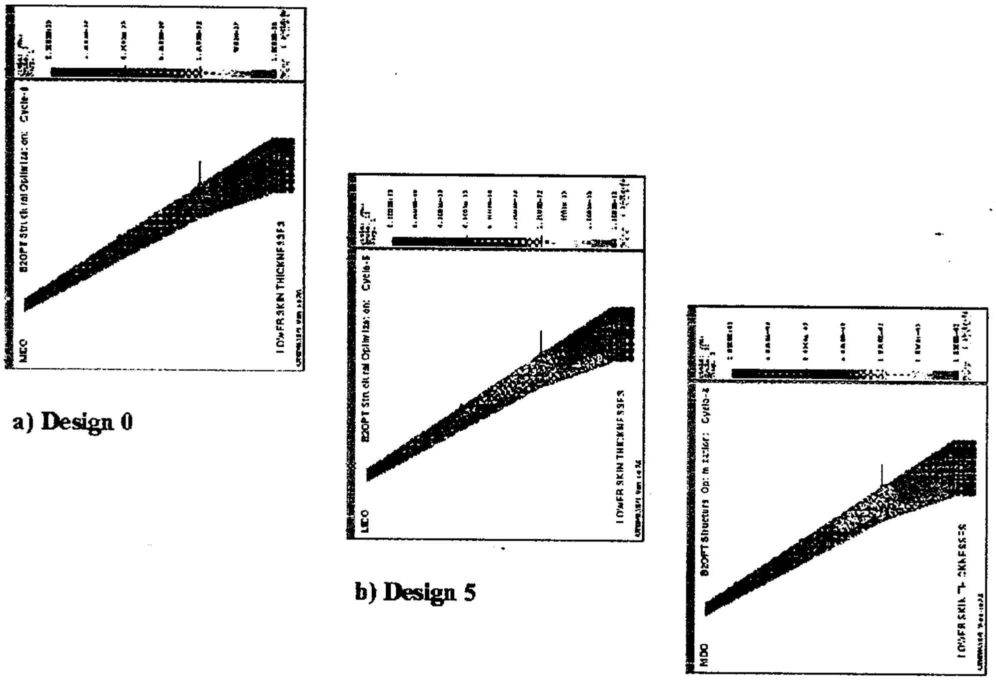
The lower skin thickness distributions as calculated by B2000 for the MDO reference wing (design 0) and the thickness/twist optimised design (design 5) and the final design (design 8) are shown in Figure 8. Design 5, the thickness/twist optimised design, shows an increase in skin thicknesses relative to the MDO reference wing (design 0). This leads to an increase of the wing torsion box



a) Designs 0-5

b) Designs 0, 5-8

Figure 7 Wave drag and circulation as function of span for Designs 0-8.



a) Design 0

b) Design 5

c) Design 8

Figure 8 Lower skin thickness distributions for the Reference Design (Design 0), the Thickness/Twist optimised Design (Design 5) and the Thickness/Twist/Shape optimised Design (Design 8). (blue: values below 10^{-3}; red: values above $1.8*10^{-2}$)

weight of 5.5 tonnes. Changes in wing thickness and twist are small when moving from design 5 to design 8. The wing crank thickness is marginally lower in design 8compared to design 5, which explains the increase in wing weight of about 600 kg. Except in the inner engine-wing attachment point, maximum skin thicknesses are found at the rear spar of the inboard wing near the crank position. This is due to the load path in a swept wing running along the rear spar of the inboard wing. The torsion box height and width decrease rapidly from root to crank, this causes the maximum skin thickness to be located near the crank position. The upper wing skin thickness distribution generally shows similar picture, although at a lower level. These lower levels are caused by differences in stress allowables between upper- and lower wing skins.

Aeronautics conclusions and next steps in the MDO activity

- Wing shape optimisation for fixed wing thickness distribution is found to have significant effect on the aerodynamic performance of the wing with little effect on wing weight. This motivates the exclusion of structural contributions to the shape perturbation sensitivities
- In the first optimisation cycles, there is a strong aerodynamic drive to a thinner inboard wing. Only after a significant wave drag reduction has been achieved, a matching opposite structural drive towards a thicker wing is encountered.
- The unusually thin inboard wing is attributed to the exclusion of wing ribs from the structural optimisation process. Higher wing weight sensitivities are to be expected when including flutter constraints. This may help to drive the design to more realistic inboard wing thicknesses. Fuel volume constraints, multi-point aerodynamic objectives, and addition of wing planform parameters may have a similar effect.

Conclusions

The ICT mechanisms have been developed concurrently with ongoing optimisation work.

The wing design study shows that the choice of design variables, and the choice of the disciplines involved will have to be re-visited repeatedly. This evolutionary aspect of MDO activities make that ICT is not just a support for the aeronautics, but is core business.

References

[Allwright-96a] S.E. Allwright. Multidiscipline Optimisation in Preliminary Design of Commercial Transport Aircraft. Ppaer presented at ECCOMAS'96, September 1996, Paris, France.

[Allwirght-96b] S.E. Allwright. Technical Data Management for Collaborative Multidiscipline Optimisation.
AIAA Conference, September 1996, Seattle, Washington, USA.

[Baalbergen-98] E.H. Baalbergen, SPINE: A practical and holistic approach to meta-computing, presented at the HPCN Europe '98.

[mdo-98] web-site
//www.telecall.co.uk/~srcbae/mdo

[van Muijden-94] J. van Muijden, A.J. Broekhuizen, A.J. van der Wees, J. van der Vooren. Flow analysis and drag prediction for transonic transport wing/body configurations using a viscous/inviscid interaction type method. Paper ICAS-94-2.6.5, presented at the 19th Congress of ICAS, September 18-23, 1994, Anaheim, California, USA.

[Sims-98] Ph. Sims, M.E.S. Vogels, S.E. Allwright. A computational framework to Support MDA and MDO. 7th AIAA/USAF/-NASA/ISSMO Symposium on Multi-Disciplinary Analysis and Optimisation, September 2-4, 1998, St. Louis, Missouri, USA.

[Vogels-98] The Information and Communication's Contribution to the MDO project. M.E.S. Vogels, S.E. Allwright, M. Stettner, Ph. Sims, and P. Bartholomew. Presented at the Royal Aeronautics Society MDO Conference, October 26-28, 1998, London, UK.