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MULTI-DISCIPLINARY DESIGN AND OPTIMISATION OF A LARGE SCALE CIVIL AIRCRAFT WING.

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Abstract

The paper describes the results obtained during a major European Union funded project which attempted to create a distributed Multi-disciplinary Design and Optimisation (MDO) system. The project involved a cooperatrion between most of the European airframe manufacturers spread across the European Union. The MDO system incorporated weight, drag and manufacturing costs as direct or quasi-direct variables and included other factors such as flutter speed considerations and stability as constraints.

The system was applied to the design of a large scale civil airliner wing of similar proportions to the A3XX. The results of the project clearly show that the approach represents an effective design methodology which can be applied to realistic large-scale design problems. It has led to the creation of a number of tools which allow the methodology to be employed in a distributed design environment.

Introduction

In the design of a major component progress along the time line usually involves the progressive increase in the number of disciplines actively influencing the decisions made. In order to control the complexity at the conceptual or preliminary design phases these disciplines are introduced into the design process using traditional simplified methods. These methods are often limited in scope and cannot provide sufficient information to assess the full implications of design decisions early in the design process. This gives rise to two serious problems. The first is that conflicts between, say, design and manufacturing requirements do not appear until resolving them is an expensive operation. The second is that it is not possible to generate designs which are optimal in a global sense. To overcome both of these problems the aeronautical design community has been developing MDO methods. These endeavour to bring together all the relevant design decision processes within a common optimising paradigm.

A number of methodologies have been advanced to implement an MDO process [1,2]. These have been deployed in the solution of a number of design problems but the scope has usually been limited. For example, the incorporation of manufacturing costs has not been considered at the same level of detail as structural and aerodynamic aspects. Nor have applications taken into account the need to accommodate design environments in which a large number of partners are cooperating in the design, manufacture and entry-into service of a major aeronautical component. This latter is typical of the design environment in Europe following the emergence of Airbus as the main manufacturer of civil airliners. A previous study by Borland et al[3] used a similar component to that adopted in the present paper but did not employ a distributed environment nor were a number of different optimisation systems and CFD codes used.

The methodology advanced here involves using a modified nested analysis and design procedure in which the Direct Operating Cost (DOC) is employed in a top-level objective function. The approach allows the trading of drag, structural weight and manufacturing costs to be directly considered. The description of the structure has a high level of detail supported by a full finite element model. The drag calculations employ a range of Computational Fluid Dynamics (CFD) codes which were run at a number of sites across Europe. Finally a novel approach for computing manufacturing costs was devised which allows the MDO system to consider detailed manufacturing aspects. The resulting system represents a unique solution to the problem of using high integrity information within an MDO system early in the design of a complex structure.

A European MDO project

During the period from 1996 until the end of 1997, a two-year European Union project (BE95-2056) explored the application of MDO methodologies to the design of large-scale civil airliner components.

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Partners in the project were British Aerospace (Project Leader), Aerospatiale, NLR, DASA, CASA, SAAB, Dassault, ALENIA, Aermacchi, HAI, DERA, ONERA, the University of Delft and the Structures and Materials group of Cranfield College of Aeronautics.

The MDO project had the overall objective of strengthening the competitiveness of the European aircraft industry and of providing a European design capability for future aircraft. In support of this development, the project partners defined a set of objectives, which stated that the project must:

- Develop and demonstrate the viability of MDO methodologies and validate them for a simplified but realistic aircraft preliminary design task.
- Investigate and demonstrate a common implementation architecture for MDO.
- Develop standards for data exchange and the solution process in order to facilitate and demonstrate industrial exploitation.
- Investigate the issues relating to the control of data exchange, implementation of cheap algorithms for the calculation of derivatives, the control of numerically intensive calculations, whilst taking full account of the overall MDO process.
- Perform multi-disciplinary analysis and optimisation combining aerodynamics, structures and manufacturing disciplines. This to include the derivation of aerodynamic and structural sensitivities, the study of design variable influence, integration of aeroelasticity, effects of the control system on the loads, structural modelling and manufacturing constraints. The MDO project should also allow a comparison of the different CFD and structural optimisation tools used by all the partners.

The success of the MDO project and the viability of a future European design capability strongly depend on close co-operation between all European aircraft companies. Multi-disciplinary design is only possible when human factors associated with teamwork; cross-discipline interaction and cross-discipline understanding are addressed. Hence, during the project, high importance was put on using teams with members from different disciplines and the organisation of multi-disciplinary workshops. Its purpose was to create a foundation to facilitate collaboration on commercial and research projects and to facilitate technology transfer within the European Community.

Problem definition MDO-project

The wing structure of the P500 was selected as the common design model for the MDO study. The P500 is a 650-seat civil aircraft precursor design to the A3XX with a wingspan of approximately 80 meters and a maximum take-off weight of 550T. The model contains three spars and has a crank at 35% of the overall wing span. Initially a wing made of aluminium was used for the studies, but optimisation has also been performed on an outer wing constructed of carbon fibre composites. Although the MDO project is mainly concentrating on the wing design, information on the overall aircraft configuration was needed to perform adequate structural, aerodynamic and aeroelastic analysis.

To support the multi-disciplinary design sensitivity study, software such as a Technical Data Modeller & Browser (TDMB) and a Multi Model Generator (MMG) were generated[4]. The TDMB contains all the aircraft and analysis information, while the MMG automates the preparation of aerodynamic, structural and aeroelastic analysis models (see figure 1). These tools ensure that all partners use the same analysis models and provide means for data exchange, comparison of results and the generation of aircraft variants.

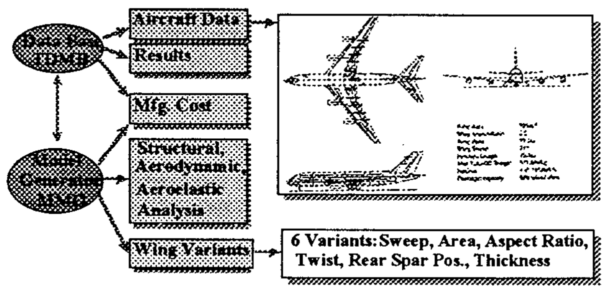

Figure 1: Overview MDO software

The overall objective of this MDO process is to minimise the aircraft's DOC. The current approach defines the DOC in terms of mass and drag parameters with factors relating to payload and range included implicitly. The process for locating the minimum DOC involves a multi-level optimisation procedure in which a number of sub-level processes feed into a top-level global optimiser. The top-level optimiser takes sensitivity information from the lower levels and makes an incremental change in the DOC in an attempt to move the design towards an optimising point. The design variables used at this level are sufficiently major to represent variants in the design configuration. Lower level design variables involve the more usual structural sizing and aerodynamic shape parameters.

A reference state design is required to start the optimisation process at which the initial values for all of the design variables at the top and sub levels are defined. In the present study this requires a reference wing with the relevant starting values is available and, as indicated earlier, an initial configuration was provided by B.Ae based on the P500.

In the approach to MDO outlined above the top-level objective function is defined in terms of the rate of change of the DOC(5). In its full form this objective function is defined by:

$$\Delta DOC = \frac{\partial DOC}{\partial Fuel} \times \Delta Fuel_{DOC} + \frac{\partial DOC}{\partial OWE} \times \Delta OWE + \frac{\partial DOC}{\partial Thrust} \times \Delta Thrust + \frac{\partial DOC}{\partial MTOW} \times \Delta MTOW \quad (1)$$

with

$$\Delta Fuel_{DOC} = \frac{\partial Fuel_{DOC}}{\partial OWE} \times \Delta OWE + \sum_{Economic-Cases} \frac{\partial Fuel_{DOC}}{\partial Drag_i} \times \Delta Drag_i$$

$$\Delta MTOW = \Delta OWE + \frac{\partial Fuel}{\partial OWE} \times \Delta OWE + \sum_{Range-Cases} \frac{\partial Fuel_{range}}{\partial Drag_i} \times \Delta Drag_i$$

OWE = Operating Weight Empty aircraft
MTOW = Maximum Take Off Weight

If the optimal mass for the aircraft is defined by m_{opt} and the drag for the reference aircraft wing is given by *drag*. For an aircraft variant i, where a parameter p_i has been varied, the optimal mass is given by m_{opt+i} and the drag by $drag_i$. Hence the variation of the empty aircraft operating weight and the wing drag with respect to the parameter changes is given by:

$$\Delta OWE = (m_{opt} - m_{opt+i}) / \Delta p_i$$
$$\Delta Drag = (drag - drag_i) / \Delta p_i \quad (2)$$

To reduce the complexity of the problem at the initial stage of the study, a simplified MDO process was defined. This process still exploits a multi-disciplinary scheme, but only uses six aircraft variants, using parameters which have a significant influence on the DOC. These 6 aircraft variants are shown in table 1 and are a mix of planform, surface, shape and structural parameters. The process required evaluating the sensitivity of an optimised wing to changes in these parameters. Taking, as an example, the weight or mass component the procedure needs to calculate a minimum weight configuration using sizing parameters for a reference wing then repeat this operation for the same wing with a small variation in one of the parameters. The numerical values computed through this process provided the inputs to the finite difference expressions at (2).

Table 1 gives an overview of these primary variants and their +3% change with respect to the reference aircraft.

Wing variants	Reference aircraft	Variant aircraft
QC Sweep	33.0°	33.99°
Area	725m²	746.75m²
Aspect ratio	8.2	8.446
Thickness	0.1	0.103
Outbd. twist	0.0°	0.25°
Rear spar position	0.65	0.6695

Table 1: Overview of the six primary wing variants.

A major feature of the Multi Model Generator is that for a variant, the whole wing layout can be automatically created. Changing the rear spar position, for example, does not only affect the rear spar but also ribs, planform shape, stringer spacing, etc.

Seven flight cases (heavy cruise, economic cruise, light cruise, diversion, pull-up, push-down and roll) were selected as they provide a representative interaction between aerodynamic, structural and aeroelastic issues and have significant influence on the DOC.

<u>Simplified MDO Process</u>

Although the original project plan envisaged using the full DOC formula described at (1) it become clear the a modified form would be required for the European MDO project to provide a tractable problem for the set time frame of the project. The modified form for the objective function is shown in Figure 2 where it is seen that the new function involves mass and drag only. The weighting factors which are included in the top-level allow the relative importance of weight and drag to be changed to reflect the balance between these two components.

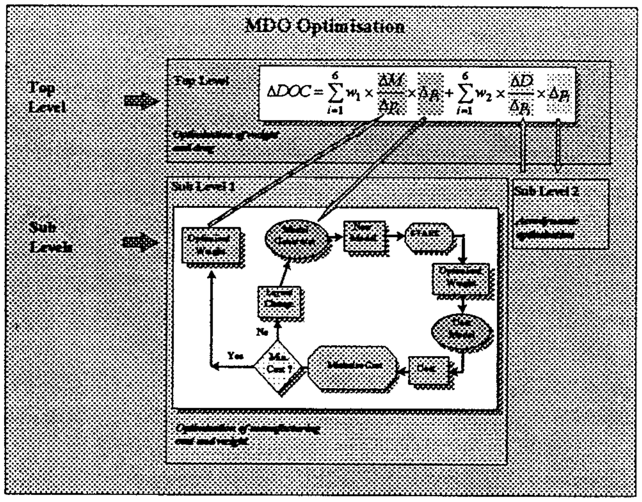

Figure 2: MDO Optimisation Process and Modified Objective Function

The MDO paradigm adopted for the solution of the wing optimisation problem is also shown in figure 2. As indicated the top level deals with the optimisation of an aircraft using the six design variables described above. The sub-levels deal with specific contributors to the top level. Thus, one of the component inputs is concerned with the ensuring that the optimiser takes into account the need to minimise the structural mass. The other sub-level seeks to minimise the aerodynamic drag.

The inner workings of the sub-level associated with structural weight and manufacturing costs is outlined in figure 2 at Sub Level 1. It can be seen that the activity in each sub-level is complex and requires a full-scale optimisation. The process in this level begins with a set of values supplied by the MMG module, which creates a structural model and the associated finite element models. MMG also supplies a set of allowable stresses which form the constraints on for the weight minimisation phase which must be performed at this sub-level. Once this information is assembled it becomes the input to a classical structural optimisation code; the one indicated in figure 2 is the DERA STARS system. The weight-minimised structure is then offered to a cost module, which examines the configuration from a manufacturing viewpoint and changes the structural layout to minimise the manufacturing costs. The layout changes have to be linked with the weight minimisation process as indicated in figure 2.

Once the optimisation process has been completed for a given wing configuration another variant is taken and a similar minimisation process is undertaken. The variants represent a 3% change in terms of the six major design parameters and by taking each of these in turn and creating the finite differences defined in equations (2) the weight differences required to construct the top-level objective function can be obtained.

The sub-level calculation processes are complex in nature, particularly the sub-process involving the combination of structural mass and manufacturing costs. Nevertheless the sub-level hands derivative information to the top-level which allows this upper level to make a step in design parameter space to generate a new set of values for the six variants. These new values can then be passed down to the sub-levels for re-optimisation and the creation of a new set of finite differences for passing back to the top-level.

The second sub-level shown in figure 2 relates to the calculation of drag derivatives for the reference wing and the six design variants. The philosophy in this level is the same as that adopted in the weight and manufacturing cost sub-level so that drag gradients for the various design variants are passed to the top-level optimiser.

These calculations were performed at a number of sites throughout Europe and represented a truly distributed design activity. Through the use of a distributed approach the aerodynamic drag optimisation was performed using a number of 3-D methods. These included a full potential method with coupled integral boundary layer; an Euler method with coupled integral boundary layer and

Averaged Navier-Stokes Multiblock method with a two-equation turbulence model. In addition, 2-D methods adapted for 3D calculations were also used to check the results and investigate the potential improvements in calculation speed.

Although the original plan had envisaged that a number of additional sub-levels would be communicating with the top-level these were not directly pursued. However, a number of additional constraints were included to account for flutter speed limits and flight stability considerations.

The basic layout shown in figure 2 represents a framework for the implementation of an MDO process. The specific implementation of this framework was different for different partners and three different approaches emerged from the project[6].

A process-oriented approach was introduced using the workflow management system SIFRAME. This was introduced by the German partner DASA and is reported in references 7. It was concluded that this system is strong when the process flow is well established but does lack the flexibility required in the early stages of the design process. In principle SIFRAME assumes that all the participating systems and data sources have been identified and that the complete MDO process has been defined before the design process commences. Whilst this is a reasonable assumption when a single partner only is involved or a design is being modified under the full control of a prime organisation it may not be appropriate in the more flexible environment of a multi-company project involving a new advanced design.

B.Ae.[7] have developed a data-centred approach which uses the B.Ae TDMB program combined with the TDMB Optimisation Solution Control Agent (TOSCA). TOSCA provides a dynamic control system which links the multi-level optimisation system into a single entity. It monitors the status of the system of the MDO process and decides on what actions to take. In this role it is acting as an agent operating as a background process controlling the execution of the product analysis tools and controlling the execution of the optimiser(s) to recommend new designs.

Finally, NLR[8] have developed the SPINE tool, which is a product which supports the realisation of functionally integrated working environment to allow users access to any tool or data set on a network. It enables sets of software and data to be integrated across a network in a fully controlled manner. In the MDO context it allows the MDO system of figure 2 to be implemented across a network under a single controlling authority or under a number of authorities. In this way the MDO process can be managed in a distributed design environment.

In addition to these specific tools provided by the project for use in the creation of a distributed MDO system individual consortium members used in-house systems to create their own MDO system which reflected the structure defined in figure 2.

Structural Optimisation Aspects

As indicated above one of the purposes of the MDO project is to allow the various partners in a major design project to employ their own design tools. Thus the partners in the project employed a variety of in-house and commercial tools including:

- MSC/NASTRAN
- ELFINI (from Dassault)
- OPTSYS (from SAAB)
- STARS (from DERA)
- B2000 (from NLR)
- ALACA (from CASA)

STARS offered a Stress-Ratioing algorithm together with a Newton based projected method. By using STARS it was possible to start the optimisation process using the Stress-Ratioing to stabilise the optimisation process before switching to the Mathematical Programming Method. STARS also offers the a dual bounding method which allows the convergence to a optimum solution to be by observing the difference between an upper and lower bound estimate of the optimal value of the structural mass. The program employed by CASA (ALACA) is different to the other optimisers in the set and is based on optimising at the detailed stressing level so that components are optimised on an individual basis.

The project agreed a basic finite element model which was generated by CASA and supplied to other partners by using MMG and TDMB. This basic model employed elementary elements which consisted of simple 4-noded membrane elements for the top and bottom skins, shear webs for the spars and ribs. These latter were supported by the introduction of bar elements in the form of vertical posts and horizontal bars which modelled the stringers. For the reference wing the model has 3022 nodes and 11386 finite elements. The engines were not directly included in the structural model thought their location and mass were represented. As indicated above the load cases for the structural model consisted of a pull-up and a pushdown manoeuvre with values -2.5 g and +1.5g respectively. The appropriate aerodynamics loads for these manoeuvre cases, taking into account the fuel state, were generated using B.Ae supplied data through the MMG. The allowable stresses also produced by the MMG were originally estimated using a simple buckling formula with a material failure cut-off value of 387 Mpa for the top skin and an agreed fixed value of 200mpa based on fatigue and damage tolerance for the lower skin. As work progressed it became clear that the absolute levels in the top skin were probable too high and that the stresses in the lower skin too low. In consequence fixed values of 300 MPa and 240 MPa respectively were implemented based on B.Ae experience.

The results for the optimised masses quoted below use the second set of allowables as the stress limits for the optimisers. However, it was recognised that these fixed values were not sensitive to aircraft design changes. In order to generate an improved set of allowables, sensitive to design changes, the Technical University of Delft's ADAS method of calculating these allowables was employed which employs a number of failure criteria. The method essentially employs a basic optimisation process allowing structural thickness to interact with the calculation of allowables. In this way it iterates to a final allowable stress set are compatible with the resulting structural sizes. These allowables now become the constraints for the full structural optimising process using the normal minimum weight optimisers and the associated thicknesses become the starting values for the optimisation runs. Although the optimised results given in this section did not use this second approach for calculating allowables, the results quoted in the manufacturing section given below and those in the more detailed description of manufacturing results given in the accompanying paper by Gantois[9] have been obtained employing the ADSA generated allowables.

The structural optimisation model employed 156 sizing variables which defined the thickness of the wing skins, the stringers and the spars. These sizing variables were selected to permit a smooth variation in structural sizes across the chord of the wing and along the span. The position and thickness of the ribs remained fixed for the purposes of the present paper but the influence of allowing variations in these parameters was explored and are reported in reference 10.

At the start of the MDO project it was generally accepted that minimum mass structural optimisation was a mature technology which would not present the consortium any problems when applied the wing structure. However, the application of standard structural optimisation codes to this realistic design problem indicated that existing methods are not entirely secure.

	B2000	**ELFINI**	**NASTRAN**
Reference	28936.0	28691.7	28749.2
Area	29331.2	29131.6	29272.0
Aspect Ratio	29218.9	29489.0	29474.4
Rear Spar	29218.9	29132.5	29213.6
Sweep	29303.0	29278.4	29281.7
Thickness	28638.9	28335.8	28482.7
Twist	29058.9	28716.6	28818.5
	OPTSYS	**ALACA**	**STARS**
Reference	28708.2	28370.0	28632.0
Area	29162.4	28816.0	29150.0
Aspect Ratio	29425.5	29016.0	29312.0
Rear Spar	29196.7	30117.0	
Sweep	29234.8	29182.0	29055.0
Thickness	28392.3	28216.0	28306.0
Twist	28761.1	28364.0	28700.0

Table 2: Optimised mass reference and variant wings all values are masses of a single wing in KGs.

Structural optimisation of the reference aircraft has given an optimised mass of approximately 28.7 tonnes. Table 2 gives an overview of the masses obtained by the different optimisers for +2.5g pull-up and the -1.5g push-down load case. It includes the values obtained for the reference wing and for the 6 variants by the main structural optimisation codes used by the project. The results displayed by STARS are, in principle, lower bounds on the results achieved by the other systems.

Figure 3 shows the changes in skin thickness of the reference wing before and after optimisation using MSC/NASTRAN. The upper figure shows fifteen spanwise zones with a constant distribution of thickness chordwise over the section. Because of the rapid tapering in wing box depth over the inboard wing, the maximum thickness is at the crank rather than at the root. The optimised wing shows that the optimisation process involves a tailoring of the chordwise thickness distribution. Skin thickness is increased in the deeper parts of the wing section where material most effectively contributes to bending stiffness.

At the start of the MDO project it was the general perception that structural optimisation was a mature technology which would give far less problems than the CFD analysis. Optimisation of this realistic design problem has however proved that even the classical structural optimisation is not totally secure. This usual assumption, that all structural optimisation codes are able to handle this class of problem, proved to be false. The fact that all of them were solving the same problem revealed that different codes gave different solutions. This was not because multiple optima existed, but because certain codes indicated a converged solution when still distant from the optimising point. Of course user experience was influential in this process of achieving incorrect solutions but the procedure for avoiding this problem was not clear.

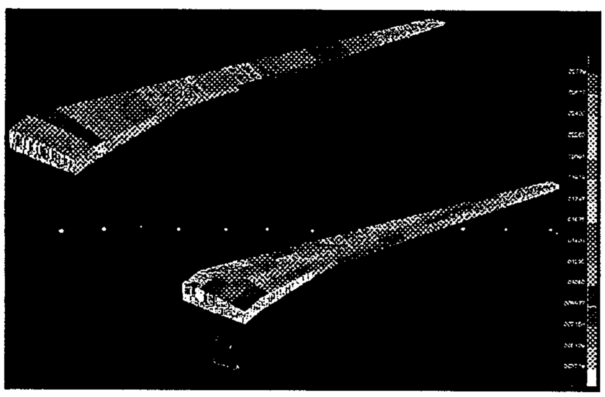

Figure 3: Top skin thickness before and after optimisation.

Hence it was not obvious which strategy should be employed for each of the optimisation programs to get a satisfying result. In order to be able to deliver the results reported above, extensive tuning of optimisation control parameters was necessary and different solution methods were used and compared.

Fortunately, the availability of different structural optimisation codes applied to the same problem allowed for extensive experimentation involving comparison of results and solution methods. In particular, the dual bounding process offered by the STARS system was a very useful aid in deciding which of the early results given by other systems were correct. Through this a reconciliation was achieved whereby all the codes eventually gave similar results as indicted in table 2.

Optimisation of the variants from table 1 and displayed in table 2 showed the following overall tendencies:

- Area change increases weight (≈ +1.8%)
- Aspect ratio change increases weight (≈ +2.5%)
- Rear spar position change increases weight (≈ +1.6%)
- Sweep change increases weight (≈ +1.8%)
- Thickness change reduces weight (≈ -1%)
- Twist change has not much effect on weight (≈ 0.15%).

All the above results took into account stress constraints only. An outboard wing made of composites was also examined and led to an additional weight saving of 3%[10].

Development approach for the MDO cost model

Having successfully developed the structural optimisation aspect of the weight and manufacturing sub-level component in the MDO process the manufacturing input was developed. The method adopted by the project employed a feature based approach using component weight, layout and manufacturing rules. This refines the traditional weight based cost model, which only calculates material cost, to a model which also takes into account assembly and detailed manufacturing cost. A fuller description of this aspect of the MDO project is displayed in figure 2 and in the accompanying conference by Gantois[9] which also provides a more comprehensive set of results.

The cost estimation process requires a definition of the product structure for the wing box and for the present application this is based on the A340; though the software allows the use of alternative product models. Once a whole product structure is defined, each of its components can be analysed with respect to its manufacturing and assembly processes. For each component there are several features which drive the component costs. These features or cost drivers can be geometrical, for example length, area, weight, or processes such as milling, drilling, or assembly features involving joints, inserts, etc.

The present application concentrates on geometric and assembly features. Thus, after identification of the relevant features, cost factors were defined either by using an estimation program or by directly assigning the values. The primary aim of the model was to have a fast tool which can accurately predict and visualise the cost changes and cost trends, when going from one design to a second. The absolute accuracy of the cost predictions was of secondary importance.

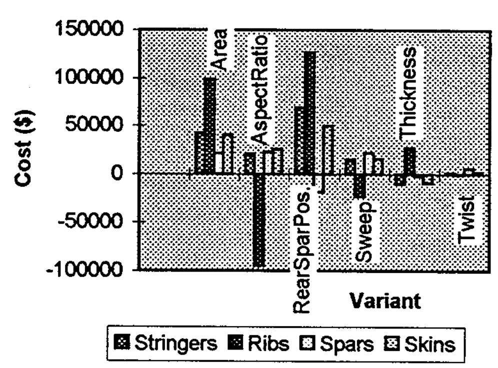

Figure 4: Cost changes of variants with respect to the reference wing.

The cost analysis was performed in two stages:

- First involves the calculation or assignment of cost factors for a reference wing.
- Second the calculation of the cost of an aircraft variant, using the reference cost factors.

Figure 4 shows the recurrent cost changes of the six variants with respect to the cost of the of the reference wing. Because the MMG is available to the components of this sub-level of the MDO process the manufacturing cost were calculated taking into account the full structural complexity of different design variants. These included both external wing geometry variants, and internal wing layout.

The incorporation of the weight module into the MDO process gave rise to a number of problems. A primary difficulty was created by the explicit link between the recurrent costs and the structural weight. As the structure is weight optimised at the sub-level there is a dependency between cost and weight, which cannot be completely de-coupled. Thus, it is not possible to have both weight and manufacturing cost within the MDO top-level. The specific top-level objective function involving weight and drag only, shown in figure 2, was adopted for this reason.

This division of contributions which places the interaction of weight and manufacturing cost at a sub-level also makes for a convenient computational programming paradigm. As indicated earlier manufacturing cost drivers are related to the internal layout of the wing structure for both the reference wing and the variants. Changes in the internal structure have very little influence on the aerodynamic performance of the wing, particularly if the wing is not considered to be fully flexible. Thus manufacturing driven layout changes can be considered at the sub-level and the wing weight minimised using STARS or a similar mainstream structural optimiser. At the top-level the overall geometry can be changed to reflect the contributions from the six design parameters which require that both structural weight and drag must interact in selecting an optimising direction for reducing the DOC. For these reasons it was decided to introduce a multilevel approach with layout changes being dealt with at a secondary level as shown in Figure 2. The specific internal structural layout changes, which were considered for manufacturing, cost purposes were changes in stringer and rib pitch. To improve computing efficiency, the structural optimisation was performed using the fully stressing algorithm of STARS.

In order to find a true sub-level optimum it was necessary to both minimise the structural weight and minimise the manufacturing costs associated with the layout parameters. This led to a secondary difficulty. Optimisers are guided by gradient information to find an optimum solution. However, for the manufacturing cost calculations required here, gradient information was not available because the changes in the manufacturing parameters were discrete. This was resolved by optimising the weight for discrete values of the layout parameters and then finding the true optimum using a quadratic interpolation algorithm. By permitting small changes only this method provided a mean to approximate discrete points by a continuous quadratic curve.

Incorporation of the Aerodynamic Sub-level

Following the basic studies related to the development of the sub-level which included the structural weight and manufacturing costs the project concentrated on the aerodynamic sub-level and the combining of these two aspects in the top-level optimiser. In view of the limited time-scale for the project an exercise was introduced which bridged the gap between the development of the independent sub-level modules and the creation of a complete system. Thus a "baseline" case was defined which represented a simplified optimisation problem involving two design top-level design variables, the "Crank thickness" and a "Tip Twist". The crank thickness was the depth of the wing at the crank position. All other sections were modified using a linear function of these variables. Artificial constraints were used to provide fixed boundaries for the optimisers:

$$0.07\text{m} \leq \text{CrankThickness} \leq 0.13\text{m}$$
$$-6.638° \leq \text{TipTwist} \leq +3.362°$$

Each of the partners used a particular aerodynamic model from amongst the list given in the section on the simplified MDO problem above. In addition, a combination of structural configurations were studied including wing alone, wing + centre section and wing + fuselage. The starting values for the complete MDO study were that the Crank Thickness had an initial value 0.1m and the initial Tip Twist depended upon the structural configuration and trim state selected. As might be expected considerable differences were noted in the outputs from these complex combinations of structural configuration and CFD methods. A detailed description is given in reference 11 and is not repeated here.

The weighting factors in the top-level optimiser in figure 2 were selected as unity; but studies employing other factors were undertaken. As might be expected the results achieved from the running a number of complete cycles of the total MDO optimisation process were influenced by the geometric configuration selected. Nevertheless, it was possible to show that taking the wing alone was sufficient if trends were being studied and absolute values were not required.

For the full results of this complex study reference should be made to Gould[11] but a number of broad conclusion emerged from the research at the stage which can be summarised as:

- the influence of drag on the optimum solution was found to be stronger than that exhibited by the structural weight due to high levels of drag on the reference geometry and the decision to maintain fixed values for the rib thickness and location
- as was to be expected the crank thickness was reduced by the top-level optimiser until the increase in structural weight became sufficiently influential at which point partners found that this thickness had reduced to between 80% and 85% of the initial value and the wing weight had increased by values from 2222kgs to 3617kgs
- The results from the studies involving the tip twist were dependent upon the geometric model selected for the aerodynamic analysis but, in any case, had little impact on the structural weight.

Conclusions

The two-year study indicated clearly that an interactive MDO method was appropriate for the overall optimal design of a complex wing structure involving structural weight, drag and manufacturing costs. All the partners in the project successfully demonstrated that this concept could be transformed into a useable multi-disciplinary process; at least for the simplified model described in figure 2. It was also demonstrated that the objective functions used both at the top- and sub-levels were realistic in coupling together weight and drag whilst allowing the influence of manufacturing costs to be felt. It was noted that for the specified cruise conditions no additional constraints were required as the weight and drag combination formed a self-constraining problem. This indicates that the MDO problem as specified and the solution process shown in figures 2 give rise to a well-posed problem. This indicates that the paradigm is adequate for further development to include all of the parameters initially targeted for inclusion in the sub-levels and more complex structural configurations including, for example, the airline fuselage.

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