Multi-cubed engineering: Multidisciplinary aircraft wing design analysis for multi objective optimisation in multi site collaboration

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Abstract: - High-tech systems are increasingly designed in collaboration of a prime contractor, acting as system integrator, and several first tier contractors. Typically multiple interacting physical phenomena influence the system behaviour. Simulations of the relevant phenomena are often performed as part of the design process, but usually only considering the phenomena of a single engineering discipline. However designing the system with respect to several objectives implies addressing all relevant phenomena simultaneously to exploit the interactions amongst these different disciplines. For each (risk sharing) contractor to be able to use the simulation results of all disciplines, the design analysis and optimisation tool suite has to be available at the contractor's respective geographic locations. Ongoing work on aircraft wing design is presented addressing such multidisciplinary analysis, multi objective optimisation and multi site collaborative engineering.

Key-Words: - Multidisciplinary design analysis, multi objective optimisation, collaborative engineering, evolutionary approach

1 Introduction

Simulation is of key importance for designing high-tech products like aircraft. World-wide competition on the aircraft market drives a need for continuous product improvement. This is reflected in the European Vision 2020 [1] which sets ambitious targets for aircraft and aero engine design. Such improvements can only be achieved by an integrated design and analysis approach based on advanced engineering and collaboration methods.

This paper describes an approach for multidisciplinary analysis, combined with multi objective optimisation and completed with initial results on multi site collaboration. Aircraft wing design is a suitable case to illustrate the concepts and to present the obtained results. Three iterations are used to arrive at the final capability. The chosen evolutionary approach [2] has the advantage of each iteration providing user value and can guide subsequent iterations. Both advantages have been observed.

The next section elaborates on multidisciplinary design optimisation and its relevance for early design phases, before explaining the implemented analysis approach. In order to illustrate the fidelity of the models used in this study, some additional detail of the structural optimisation is provided. Selected results illustrating multi objective optimisation are provided. The last section describes the multi site collaboration before presenting the conclusions.

2 Multidisciplinary design and optimisation

NASA [3] defines multidisciplinary design and optimisation (MDO) as a methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena. The American Institute of Aeronautics and Astronautics (AIAA) [4] more informal definition is "how to decide what to change, and to what extent to change it, when everything influences everything else." The AIAA white paper [5] characterises multidisciplinary design and optimisation 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.

As wing design is an inherently multidisciplinary activity including analyses in disciplines like aerodynamics, structures, flight control, manufacturing, etc. This succinctly holds for the objectives of the wing case study.

In many high-tech systems, most of the total life-cycle costs are fixed during the early design, even though the costs are actually accrued much later in the life cycle (shown in Fig. 1 which is based on aircraft data from [6] complemented with general domain information from [7]). As early design decisions determine most life-cycle cost, the presented case study pertains to the early phases of aircraft design. In stead of the semi-empirical rules traditionally relied on, progress in standard computing platforms and theoretical advances currently allow for more accurate physics based modelling and numerical methods to simulate conceptual aircraft designs with increased fidelity [8] within reasonable time. With new aircraft needing investments of up to 10 billion Euros [9], even small improvements as depicted in Fig. 1 are important.

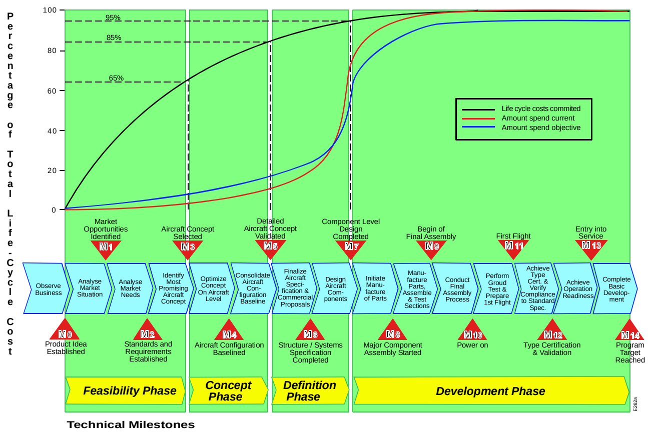

Fig. 1 Relative amount of costs fixed and spend during life-cycle based on aircraft data from [6] and general domain information from [7].

At system level, traditionally the knowledge and experience of the human designers involved is used. It is common for a designer to focus on a single discipline. The interaction amongst the disciplines involved in wing optimisation, for example between aerodynamics and structures, is reflected in the interaction between the human experts. A typical sequence would be the aerodynamics expert designs a wing surface using dedicated computer-based models and tools. The aerodynamic forces are passed to the structures expert who subsequently optimises a feasible structure design for this wing geometry, using his own dedicated computer-based models and tools. This result can be transferred back to system level and then on to the aerodynamics expert. Due to the human experts involved, a system level iteration typically takes a few weeks to a month to complete. Nevertheless the success of modern aircraft testifies to the effectiveness of this way of working. However the increasing requirements on aircraft performance and consequently on its design, as worded as part of the European Vision 2020 (Argüeles et al) [1], justify the investigation of a different, more innovative design optimisation approach. Also the addition of more disciplines, e.g. taking manufacturing concerns or environmental impact into account, is stretching the current way of working to “synergistically exploit mutually interacting phenomena [3]”. The presented work aims to couple the key disciplines involved in the aircraft wing design process by integrating the dedicated design tools used. Next a suitable optimiser is coupled to explore a part of the design space to arrive at an optimum with respect to the defined objectives.

For a single wing optimisation, 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 wing design and the many interacting disciplines involved. Various discipline experts are still needed to select proper parameters, to define a suitable initial design and to judge the feasibility of the generated results for the disciplines which are not (yet) taken into account, so the wing design capability confirms the applicability of the human-centred approach of [5].

3 Top-level wing analysis

Figure 2 depicts the top-level view of the wing multidisciplinary analysis capability, the result of the first iteration.

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 Fig. 2, 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 and hence also minimum emissions. Some of the major top-level components are succinctly described below.

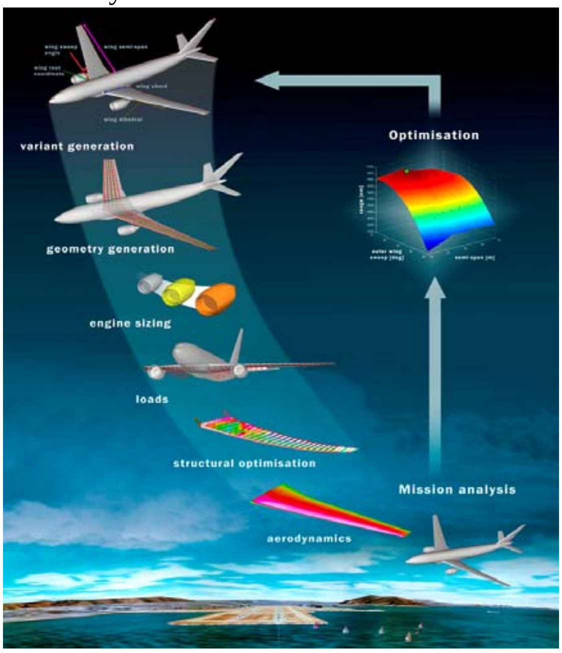

Fig. 2 Overview of the multidisciplinary wing analysis capability

The *variant generation* component (see top left picture in Fig. 2) uses a number of parameters to define a wing-geometry resulting in the external wing geometry, for aerodynamic analysis, and the internal wing geometry structure, as needed for finite element structural analyses and optimisation.

For *engine sizing* (third picture in Fig. 2) a scalable engine data set is being used to determine the engine weight and the corresponding fuel flow for the take-off thrust. This is also referred to as a "rubberised engine" model. If required the engine sizing component can be replaced by more detailed simulation, illustrating MDO's adaptive characteristic [5].

The *structural optimisation* component (fifth picture in Figure 2) determines the thickness of the wing's primary structural elements like spars, ribs and wing skin. For this, Finite Elements Methods (FEM) tools on standard desk-top computing equipment are used. The next section will elaborate on this. For the *aerodynamics* component (sixth figure in Fig. 2) a Computational Fluid Dynamics (CFD) full-potential boundary layer calculation for the cruise phase is performed determining the wing's key aerodynamic characteristics. Future, more advanced, multi-level evolutions of this component could take other relevant flight phases into account. Another partner has integrated a commercial flow solver, again illustrating how adaptive the analysis capability is [5].

The last component, in the bottom left part of Fig. 2, 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 derive the design parameters of the next iteration of the wing variant. All models exchange their data via an Integrated Design Model (IDM), ensuring consistency between the key parameters in the various models of the multidisciplinary analysis capability.

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

4 Structural optimisation

The Structural Optimisation component sizes the wing primary structural elements like spars, ribs and covers, based on certain representative load cases. In principle, all load cases required to certify the aircraft structure according to the US Federal Aviation Regulation (FAR 25) rules [10] 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 2 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 and full fuselage tank.

The structural optimisation is detailed in Fig. 4. This local-level optimisation loop interacts with the various analysis modules from the other disciplines via the IDM. 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 of the +2.5*g* pull-up manoeuvre are updated for the new aircraft weight.

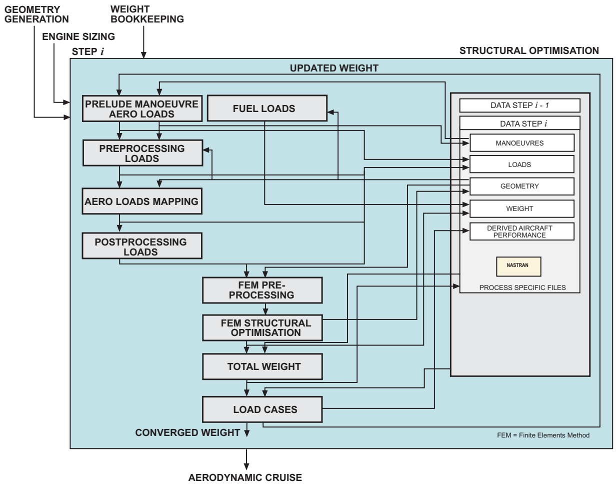

Fig. 3 Details of structural optimisation process.

The *prelude manoeuvre aero loads* module (see box in Fig. 3) provides the aerodynamic loads by calculation of the flow solution according to an extension of the non-linear lifting line method [11]. 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 Fig. 4.

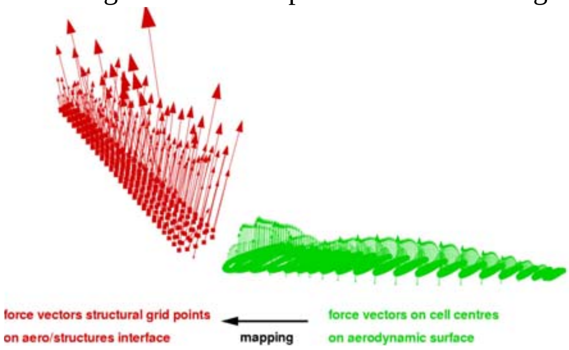

Fig. 4 Example of component interaction, mapping aerodynamic forces to structural grids.

The wing structural layout, as provided by the *geometry generation* 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 those structural elements into design areas and inserts 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 set for the subsequent structural analysis step. For the engines, data including weight and thrust forces from the engine-sizing module are used.

The structural analysis uses FEM tool 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 Fig. 6 this involves 748 elements grouped in 130 design regions. The optimisation minimises the total wing weight by varying element thicknesses and limiting maximum von Mises stress. The optimisation is performed using NASTRAN's gradient based SOL200 optimiser, which directly controls the linear static FEM analysis. The optimisation analysis converges in approximately 20 iterations. Some results of the optimised wing structure are given in Fig. 5 below.

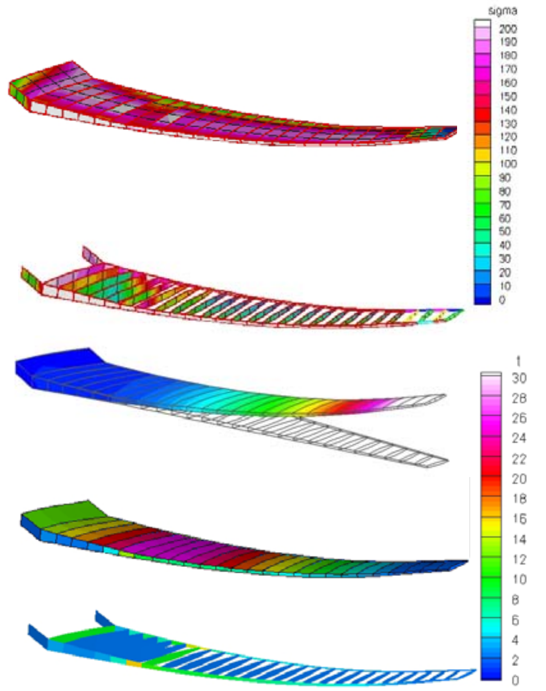

Fig. 5 Von Mises stresses at +2.5 g manoeuvre for wing skin (top) and wing internal structures (second from top). Wing thickness optimisation results at +2.5 g manoeuvre for internal structures (bottom) and wing thickness (second from bottom). The maximum wing deformation at +2.5 g manoeuvre is shown in the middle.

The thicker rib in the inner wing (and the adjacent beam sections) is where the engine weight and thrust forces are transferred. Towards the wing tip all ribs are limited to the minimum thickness without reaching the maximum Von Mises stress. 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.

During the *global-level* wing planform optimisation (Fig. 2), 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 Fig. 3, the wing weight is observed converging about one order of magnitude. More information on the wing optimisation is provided in [12].

5 Multi objective optimisation

The multidisciplinary design simulation elaborated in the previous section typically takes in the order of one half hour to perform a full analysis of a single wing design. The computational fluid dynamics analysis consumes most time even when executed on a dedicated computer, with the structural optimisation running in parallel on a standard 2 GHz PC platform. All other analysis use much smaller amounts of computational resources.

The optimisation algorithm needs to evaluate many different wing design analysis to reach the optimum design. In order to accelerate this optimisation, a meta-modelling approach is used. The wing designer determines the relevant part of the design space for the wing parameters involved. This design space is sampled with a number of wing design points commensurate with the accuracy of the analysis models used i.e. for each design point the multidisciplinary analysis is performed. By fitting a suitable approximation for a selected number of properties of each design point a meta-model of the data is obtained. Note that as the full Integrated Design Model is available for each wing design point, any stored characteristic can be used as an objective function for which a fit can be made. Fig. 6 illustrates the original data and the meta-model, in this case for the calculated range as design objective. Various fit functions have been used. Those yielding the most accurate fit (Kriging, 4th order polynomial) are shown in Fig 6. More info on the fitting tool used can be found in [13], [14]. Using the resulting fits (or response surfaces), various optimisation algorithms have been used. All algorithms provide similar results when taking the accuracy of the models into account. These results have also been included in Fig. 6. As can been seen, a substantial range improvement can be obtained with respect to the reference wing design. This optimal design point has been verified by using the full analysis capability for the optimum wing design.

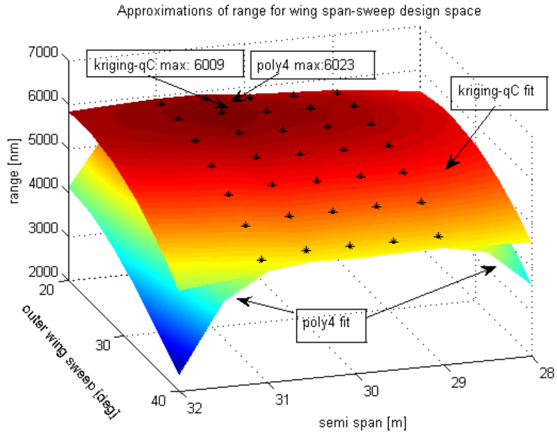

Fig. 6 Response surface for range as objective function for two design variables (wing sweep, wing semi span), two fitting functions (Kriging, 4th order polynomial) and optimum wing design points found.

The wing design with optimum range also consumes much fuel so a multi objective optimisation is performed by simultaneously maximising range and minimising fuel consumption. The resulting Pareto front comprises those designs, where further improving one objective will reduce the other objective. A genetic algorithm determines the various points delineating the Pareto front. More detail on the specific algorithm used is contained in [14]. As can be seen in the top right part of Fig. 7, in the original set of wing design variants, adding fuel reduces range. The Pareto front contains wing designs for which adding fuel increases range, as expected. The Pareto front allows choosing a range, for instance 5200 nm, and determining the corresponding optimal wing design.

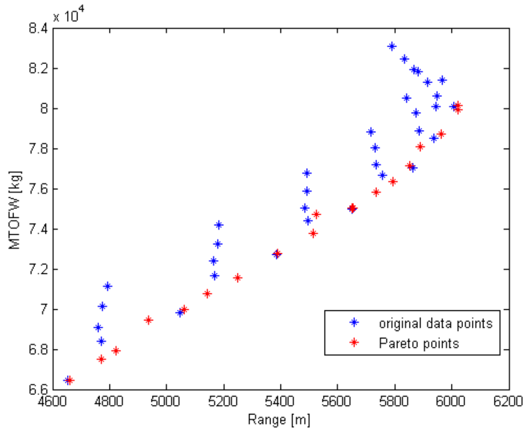

Fig. 7 Original wing designs (blue) with respect to both design objectives (range, Maximum take Off Fuel Weight) and the obtained Pareto front.

Sometimes a combined objective function can be constructed. In this case fuel efficiency has been chosen. Due to the consistency between and interaction of the integrated models of the design analysis, fuel efficiency is a trade-off between range and fuel weight, with all fuel used to obtain maximum range. Fuel efficiency has economic relevance as well as environmental relevance (reduction of emissions). A single objective optimisation has been performed. The result is provided in Table 1.

Design	Wing Span (m)	Wing Sweep deg	Range (nm)	MTOFW (kg)	Fuel Efficiency (person km/l
Original design	30,00	33,00	5 484	75 006	27,08
Maximum range	30,68	23,27	6 023	80 159	27,83
Pareto Point 5200 nm	30,99	34,32	5 247	71 561	27,16
Maximum fuel efficiency	32,00	27,45	5 721	74 026	28,62

Table 1 Wing design parameters and selected key characteristics for several wing designs (original design and several optimisations).

Table 1 shows that different objectives lead to different designs with significantly different properties. This illustrates the power of multidisciplinary analysis tools combined with multi objective optimisers for expert designer. It also shows that such tool suite do not offer an alternative to expert knowledge. A suitable initial design has to be selected. Also the wing model has nine parameters, of which the relevant ones have to be selected for optimisation. For many design parameters, which in practise is more then three, extracting meaning from the Pareto results is hard. Fig. 8 shows the wing designs which form the Pareto front in Fig. 7 depicted in design parameter space.

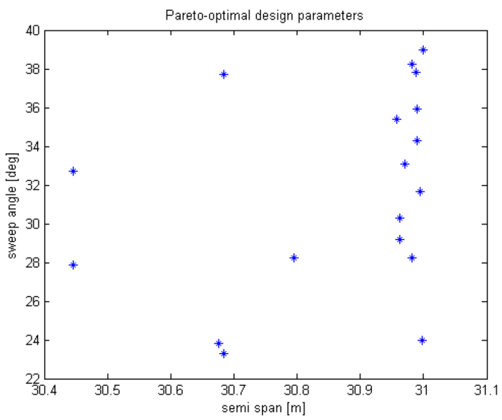

Fig. 8 Wing designs forming the Pareto front depicted in Fig. 7 in design space.

Combining the multidisciplinary analysis of the first iteration, with the multi objective optimisation is the result of the second iteration of the evolutionary approach used in this study. The next section describes initial progress towards multi site collaboration, the main target of the third and final iteration of the described work.

6 Multi site collaboration

For many competitive, high-tech products significant part of the product value is provided by suppliers. With 60% supplier content, aircraft are no exception [15]. The prime contractor acts as system integrator, closely cooperating with the risk sharing first tier suppliers. This requires close collaboration, also during the design phases. Consequently capabilities like the wing MDO need to be available to all partners of the networked collaboration. Due to the risk sharing nature of the collaboration, partners prefer to use their own tool suite at their own premises. Distributing the entire capability amongst all partners is impeded by limitations on (commercial or proprietary) tools. Such limitations include variation in computing platforms, IPR and increasingly tight security policies. A solution is needed for flexibly combining partner's assets into a shared capability with convenient access by design experts, who often are no information technology experts, at their local offices.

Fig. 9 illustrates a possible solution for a geographically distributed version of the wing capability described above. The wing designers initiate the analysis process by specifying the design (i.e. the wing geometry parameters) in the IDM, which is implemented as a text file. The IDM is uploaded to the wing capability using a web service. The web service initiates the analysis by executing the *geometry generation* process. Upon completion the web service returns selected results (e.g. the relevant IDM part and a graphic presentation of the geometry) to the designers for inspection on their standard desk top computer. Once the designers are stratified with the geometry results, another web service submits the IDM, depicted by the dotted lines in Fig. 9. The remaining analysis of the full wing capability will be executed, upon completion returning the results to the designers. In case one of the subsequent tools needs to be executed at a specific partners site, this can be performed similarly to the geometry generation process described above, without any noticeable difference to the designers involved. Key assumptions are that all relevant data are exchanged via the IDM and that, for restricted tools, the owners provide the engineers with access via their web pages. Although initial trials have been performed, the third iteration comprises full implementation of this multi site capability. Completion will finalise the multi cubed facility referred to in the title.

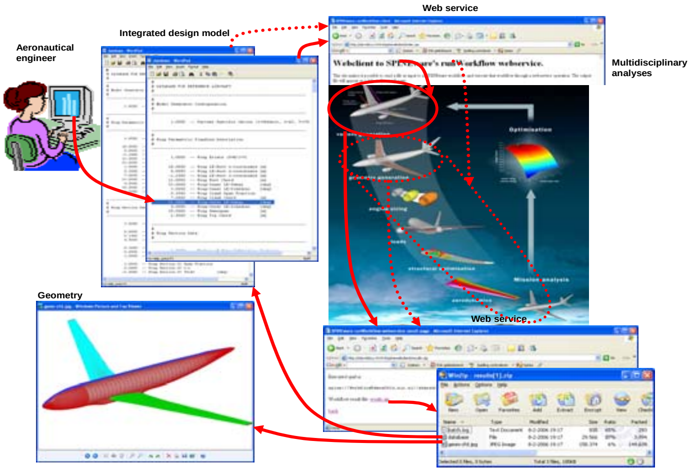

Fig. 9 Illustrating an option for geographically distributing the wing design capability.

7 Conclusions

In high-tech systems simulations are becoming available for use in the early design phases, which determine the majority of the system's total life cycle costs. By combining the simulations of various interacting disciplines, multidisciplinary design analysis allows designers more consistent and swifter assessment of their designs. It also allows deploying multi objective optimisation providing expert designers with valuable insight in design trade-offs. Enabling remote access to tools of collaborating partners will significantly improve the collaborative engineering process for geographically dispersed teams, while respecting the IPR of the programme partners.

Using the evolutionary approach, the first two iterations realised the first two objectives, with the current (and last) iteration aiming at adding the multi site aspects to arrive at the envisaged multi cubed facility for aircraft wing design.

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