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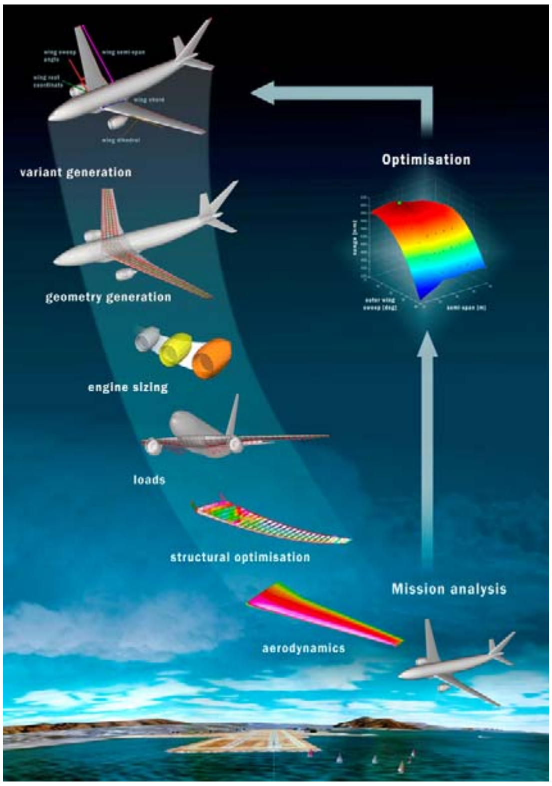
Executive summary

Advancing the state-of-the-art in civil aircraft design: a knowledge-based multidisciplinary engineering approach



Top-level wing multidisciplinary analysis capability based on consistent design description

Problem description
The early phases in aircraft design allow much freedom to optimise the aircraft by synergistically exploiting the mutually interacting phenomena of the disciplines involved, i.e. use Multidisciplinary Design Optimisation (MDO) combined with knowledge-based engineering. As can be seen in the figure, these phases also determine the major part of the total life cycle costs. Two MDO examples are elaborated, wing design and design of an engine disc.

Description of work
For wing design the disciplines involved in the include geometry generation, engine sizing, structural optimisation and aerodynamics.

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Knowledge management

This report is based on a presentation held at the ECCOMAS CFD conference, Egmond aan Zee, the Netherlands, 5-8 September, 2006.

For engine design the disciplines involved include geometry generation, meshing, thermal analysis, stress analysis and lifing.

Results and conclusions
An initial multidisciplinary design framework has been realised for both wing and engine design. Such initial capabilities demonstrate the feasibility of the multidisciplinary design approach for aeronautical design. The resulting design optimisations testify to the advantages of multidisciplinary design optimisation approach.

Applicability
Both examples demonstrate NLR's capability to integrate existing tools into a multidisciplinary design tool chain. Availability of such tool chains can support the Dutch industry to offer more integrated services, thereby providing increased added value.

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Advancing the state-of-the-art in civil aircraft design: a knowledge-based multidisciplinary engineering approach

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Summary

To design better aircraft and engines, co-operation is of prime importance. In aircraft design Co-operation has many facets, such as the involvement of experts in various disciplines that work together and share their specific knowledge. Often such experts are employed by different companies and are thus geographically dispersed.
The early phases in, for instance, aircraft wing design allow much freedom to optimise the wing by synergistically exploiting the mutually interacting phenomena of the disciplines involved, i.e. use Multidisciplinary Design Optimisation (MDO) combined with knowledge-based engineering. Disciplines involved in the multidisciplinary wing design analyses include geometry generation, engine sizing, structural optimisation and aerodynamics. Engine design uses MDO at various system levels to enable the knowledge-based engineering. The disciplines involved include thermodynamics, aerodynamics and structural optimisation. Various partners co-operate in the design of such complex systems. This requires multi-company access to the multidisciplinary analyses capability, for which current progress is described.
An overview of the current MDO state-of-the-art will be presented to illustrate how the mentioned MDO cases are advancing the state-of-the-art. Both MDO cases are elaborated to elucidate the MDO capabilities, the evolutionary approach taken and the knowledge generated. Initial results are shown.

Contents

Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
CFD	Computational Fluid Dynamics
CAD	Computer Aided Design
COTS	Commercial Off The Shelf
IDM	Integrated Design Model
IPR	Intellectual Property Rights
IT	Information Technology
MDO	Multidisciplinary Design Optimisation
PDM	Product Data Management
VIVACE	Value Improvement through a Virtual Aeronautical Collaborative enterprise

1 Introduction

This paper provides an overview of the work being performed to advance the state-of-the-art in Multidisciplinary Design Optimisation (MDO) in aircraft and engine design. Based on aircraft design characteristics, the second chapter justifies the need for improved knowledge during the early design phases and hence the need for improved MDO. The third chapter elaborates the current MDO state-of-the-art and the improvement being realised, in relation with collaborative engineering as currently being practised in the domain. Chapter 4 discusses the MDO for wing design. Chapter 5 does the same for engine MDO. To illustrate the evolutionary approach taken, both chapters are split in separate sections for the first iteration and the second iteration. As multi-site multi-company collaboration is common in the both domains, chapter 6 discusses progress on the geographically dispersed access to the MDO facilities, taking the wing MDO as an example. The conclusions are provided in chapter 7.

2 Aircraft design process characteristics

The traditional approach for the aircraft design process is to perform an exploration of the design space at top level during the early design phases, using heuristics or simplified tools like spreadsheet interpolation. The resulting initial top-level design produces a preliminary allocation of targets for each discipline considered relevant at this level. Subsequently each discipline performs an initial design iteration guided by the results of the top-level design. These initial results are fed back to the top-level design. Typical target times for an iteration during this phase are weeks to a month[1]. Once the top-level design is chosen, the conceptual design phase is entered (as indicated in Figure 1), where the same top level and discipline level activities are carried out for the major systems, like the wing, but using more accurate and hence more time consuming methods and supporting tools. Once the concept is defined, the definition phase is entered, where each discipline uses its full precision tools and methods for the subsystems involved (e.g., details like the stiffeners for a fuselage panel are considered). The many aircraft flying today testify to the viability of the current practice of aircraft design, with its many disciplines like aerodynamics, structures, engines, thermodynamics, avionics, economics. However fierce international competition implies the need for reducing the time-to-market and increasing the affordability.

Figure 1 illustrates the aircraft industry's characteristic that the choices made during early design phases already determine the majority of the total life-cycle costs of the aircraft. The majority (65%) of the total life cycle costs are already determined during the feasibility phase, increasing to 85% in the concept phase. A similar relation holds for example for the aircraft engines and for the space domains, indicating that the described work has relevance to other domains. Because of the early cost allocation, there is an incentive to improve the available knowledge about the complete product to be developed and apply it as early as possible in the product's development process. Therefore this paper focuses on these early design phases.

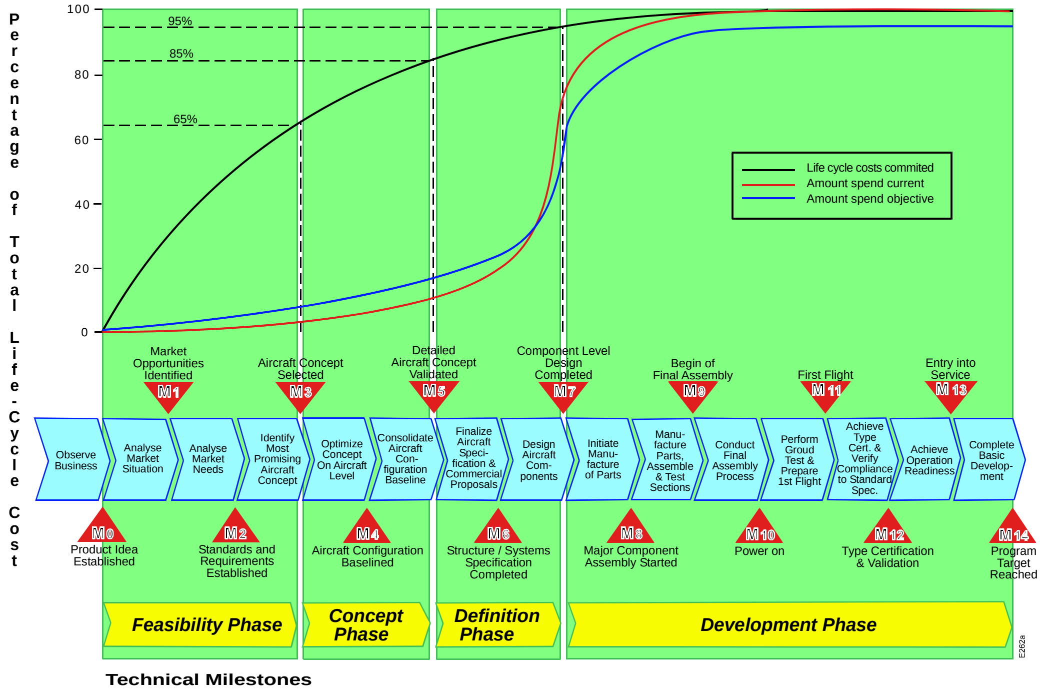

Figure 1 Relative amount of total Life-Cycle Cost during the aircraft lifecycle phases (committed cost data taken from[2], technical milestones from[3], cost spend data taken from[4].)

Aircraft design and manufacturing involve significant financial investment of up to 10 billion Euros for new large commercial aircraft like Airbus A380 or the Boeing 787[5]. These investments and associated commercial risks reinforce the need to increase the knowledge of the product characteristics in the early design phases. As the major disciplines involved are already mature, attention in this paper focuses on multidisciplinary approaches for further improvements.

3 Multidisciplinary design and optimisation

To improve the reliability of the predictions of the properties of the envisaged aircraft in the early design phases, and hence to better predict the total life-cycle cost, the collaboration among the mono-disciplinary experts of the various partners must be effectively intensified. This will enable the aeronautical engineers to perform multidisciplinary analyses of their own design variant with (automated) access to the results from other disciplines. This can be achieved by improving accessibility of models, data and tools to the various discipline experts involved. NASA[6] defines Multidisciplinary Design 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)[7] more informal definition is "how to decide what to change, and to what extent to change it, when everything influences everything else." In the AIAA white paper[8] multidisciplinary design 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 (see also Figure 1);
- 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.

Figure 2a, modified from[8], shows a taxonomy of various forms of MDO. On the horizontal axis of Figure 2a the multidisciplinary design optimisation level is defined. Trade-off studies produce single design points generated and graded relative to each other without formal optimisation. Limited multidisciplinary design optimisation indicates a disciplinary sub-optimisation or optimisation with limited disciplinary interaction. Full multidisciplinary design optimisation indicates system (e.g. aircraft or engine) level optimisation with most critical disciplines involved in a consistent manner. For example computationally expensive high fidelity Computational Fluid Dynamics (CFD) tools can take hours or days to compute a flow around a single aircraft configuration based on very detailed specifications. This is incompatible with the response time requirements of design sessions for the earlier phases of the design. Also during such design sessions, the specifications are not yet sufficiently frozen and detailed for such tools. The objectives during the early design phases are to determine the robustness of a concept rather the finding a solution which is optimal, but for a limited design space only. This implies the need for computationally efficient models which represent the characteristics of the full precision tools. The diagonal in Figure 2a represents the current state-of-the-art. Full MDO is usually performed at system level in the early design phases, with full precision models only being feasible for component design within a chosen concept.

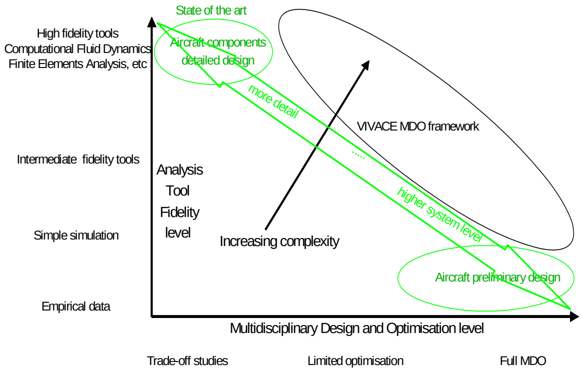

Figure 2a MDO taxonomy and state-of-the-art

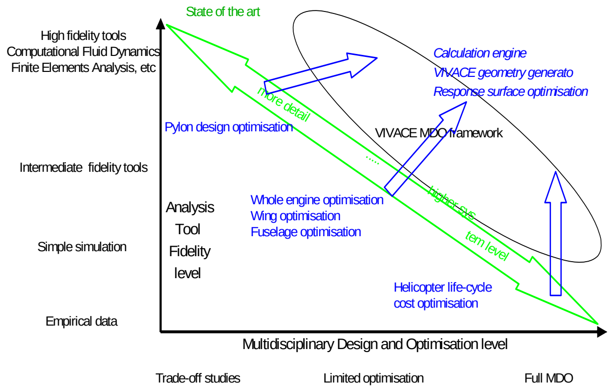

Figure 2b Advancing the MDO state-of-the-art

The Value Improvement through a Virtual Aeronautical Collaborative enterprise (VIVACE) initiative is launched to improve the state-of-the-art. VIVACE comprises over 60 partners. Figure 2b shows how various parts contribute to advancing the current state-of-the-art. The calculation engine[9], the VIVACE geometry generator and the response surface optimisation[10] are generic tools, applicable to various MDO applications. Helicopter life-cycle cost optimisation is an example of full MDO at top level early in the design phase[11] which increases the fidelity of some of the disciplines involved, in this case related to life-cycle costs. On the other end of the scale, the pylon design optimisation[12] improves the integration with some other disciplines. The fuselage optimisation, wing optimisation and engine optimisation are somewhere in between, aiming to increase the number of disciplines as well as increase the fidelity of the models used. The latter two cases are elaborated below.

In order to better understand the elaborated case study, first some general definitions are given. Concurrent Engineering is defined in[13] as “a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirements”. The concurrent engineering approach is based on five key elements[14]:

- a process;
- a multidisciplinary team;
- an Integrated Design Model (IDM);
- a dedicated concurrent engineering facility;
- a software infrastructure.

In aerospace traditionally a waterfall approach is used. The advantages of the waterfall approach include its well understood behaviour and its compatibility with the management of large teams. Disadvantages include results becoming only available at the end of the project, at which time the intended users are limited in their possibilities to influence the results. Also the long time-to-market implies it is difficult to accommodate evolving user requirements and to follow the changes in the environment.

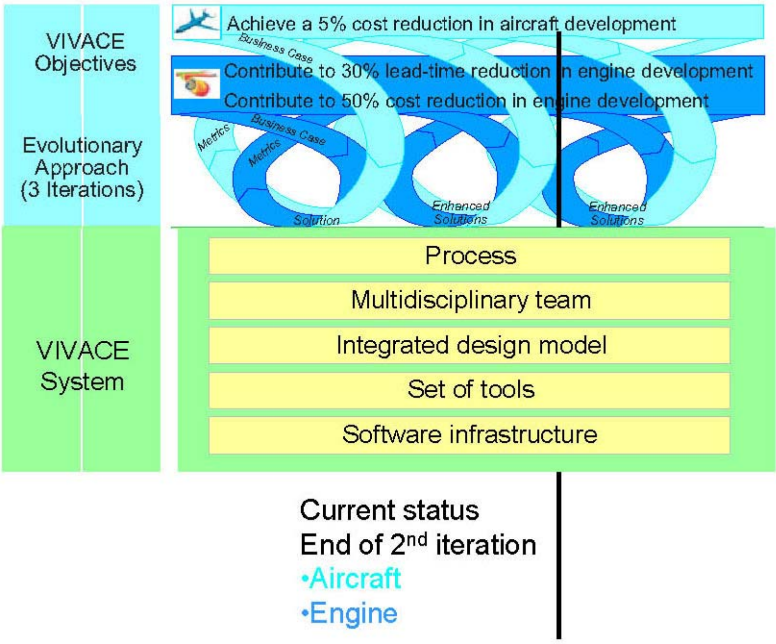

Figure 4 VIVACE evolutionary approach

Evolutionary management[15] focuses on continuous intermediate deliveries that provide user value. The resulting user feed-back is used to guide further system development. Taking this evolutionary approach into account, VIVACE uses three main iterations, while allowing for intermediate minor iterations at VIVACE system component level (see Figure 4). The next chapter elaborates MDO combined with collaborative engineering for wing design, based on an evolutionary approach.

4 Wing MDO case

4.1 Wing multidisciplinary design analysis

Figure 5 depicts the top-level view of the wing multidisciplinary analysis capability. The wing optimisation is based on a multi-level optimisation, i.e. within the top-level full-wing analysis and optimisation as shown in Figure 5, some of the lower-level analyses processes also include optimisation loops. For example the engine-sizing process optimises the thermodynamic cycles to arrive at minimum fuel consumption. Below some of the main components at the top-level are briefly described. The geometry generation component uses a number of parameters to define consistent wing geometric models for the different analyses. The available parameters are depicted in Figure 5 the top left labelled “variant generation”. The generated geometry represents the wing external geometry, for aerodynamic analyses, and the internal wing geometry (shown in the part labelled “geometry generation” in Figure 5) represents the internal wing structure as used in the finite element based structural optimisation. For the engine sizing, labelled as such in Figure 5, a scalable engine model (also referred to as a “rubberised engine”) is used to determine the engine weight and the corresponding fuel flow from the (maximum) thrust requirement as evaluated at take-off condition. The structural optimisation component makes use of the commercial software MSC Nastran[16], and determines for a +2.5g manoeuvre load case, the optimal thicknesses of the wing’s primary structural elements such as spars and ribs. This is achieved by automatic minimisation of structural thicknesses while maintaining local von Mises stress below its allowable value, applying linear static analysis for the stress prediction. A result of this structural optimisation is shown in the part labelled “structural optimisation” in Figure 5. Also for the wing skin thickness a structural optimisation is performed. For the aerodynamics cruise component, an NLR proprietary simulation system is used. A full potential/boundary layer Computational Fluid Dynamics (CFD) simulation of the wing-body configuration is done for the considered Mach 0.8 cruise condition. Figure 5, lower left part (labelled “aerodynamics”) depicts the result. The last component in Figure 5 is mission analysis. This component combines some key characteristics of the wing design, as obtained from the previous components, into a typical mission result like range. Such a mission result constitutes the characterisation of the design, which can be used for subsequent optimisation, as depicted in the figure 5. The analysis capability is obtained in the first iteration (refer to figure 4). The user value accrued confirms the value of achieving the objective of the evolutionary approach.

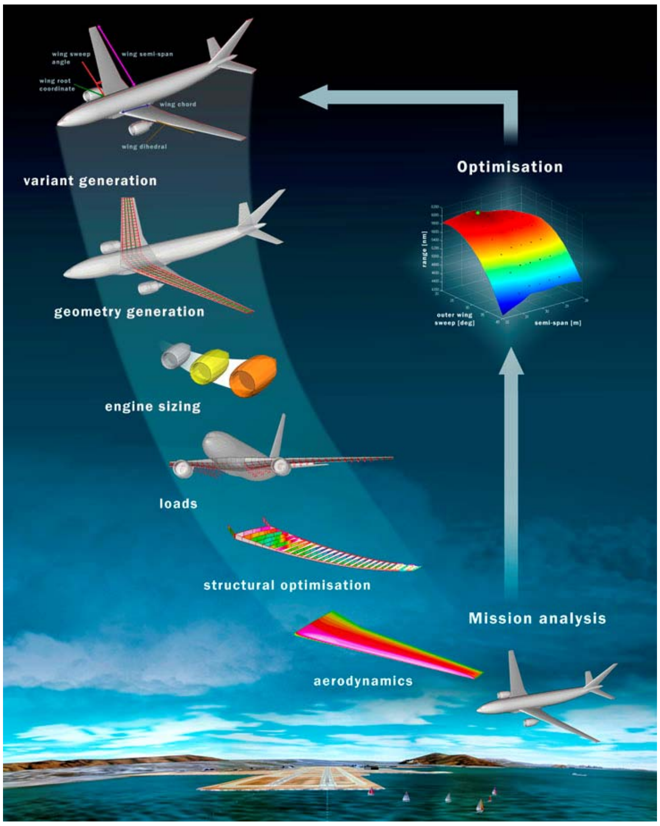

Figure 5 Top-level wing multidisciplinary analysis capability

4.2 Wing optimisation

The wing analysis capability captures a significant amount of knowledge from various disciplines. Knowledge is commonly understood as meaning a “fluid mix of framed experience, values, contextual information and expert insight that provide the framework for evaluation and incorporating new experiences and information” [17]. Some of the work described below, performed in the second iteration, demonstrates how the wing multidisciplinary analysis capability contributes to knowledge-based engineering, part of knowledge management. As the term knowledge management might cause confusion, the following definition captures the major elements. “Knowledge management is the systematic and organisationally specified process for acquiring, organising, and communicating knowledge of employees so that other employees may make use of it to be more effective and productive in their work” [18].
Expanding on the first iteration wing design capability, for the second iteration an optimisation strategy has been implemented. Performing an analysis of a wing design variant on specific computer network, including specific computer architectures, takes around 1500 sec for a single multidisciplinary analysis. In the second iteration, work started on a computationally more efficient optimisation strategy. The relevant wing design space is initially explored using a course grid of 35 wing designs. Subsequently a response surface is fitted through the design analysis results. Next an optimisation is performed using the response surface instead of the full

precision analysis results of the intermediate designs needed by the optimisation to determine the most promising design region. Subsequently for this design region more time-consuming full wing analysis can be performed. The results of this optimisation are provided in the box on the right side of Figure 5 labelled “optimisation”. The full information on this optimisation is provided in[10]. The personnel performing the optimisation do not need to be experts in the disciplines involved in the optimisation, demonstrating that the wing optimisation capability indeed accounts for knowledge-based engineering.

5 Engine MDO case

For the engine MDO case also the approach for the first and second iteration are provided, to illustrate the user value generated by adhering to the evolutionary approach.

5.1 Single-level engine multidisciplinary design optimisation

The objective of the first iteration is to set up multidisciplinary analysis and optimisation processes for two engine components. The optimisation process for a high-pressure turbine disc focuses on the thermal and mechanical disciplines, whereas the optimisation process for the compressor blade focuses on the aerodynamic and structural disciplines. In the presented multidisciplinary analysis and optimisation taxonomy (Figure 2), the first iteration implements limited optimisation.

In the first iteration, the partners involved will integrate their standard commercial and proprietary tools for multidisciplinary analysis and design of their respective components into collaboration frameworks that support the automation of the analysis processes. Such frameworks contain facilities to support collaborative engineering over multiple sites, which could be required in future iterations. To provide early user value, the objective of the first iteration is scoped at a single component and a single partner. The objective of the first scenario is to address the support of these collaboration frameworks for the analysis and optimisation. The resulting frameworks will fit with the present industrial way of working, providing immediate user value.

The first iteration already requires applying advanced multidisciplinary design and optimisation technology. This concerns the parameterisation in the (proprietary and Commercial Off The Shelf (COTS)) Computer Aided Design (CAD) tools, of the high-pressure turbine disc and the compressor blade. This is similar to the “variant generation” process of the wing case in Figure 5. Parameterisation entails describing the entire design by a limited number of parameters. These parameters are the input, which the automatic optimisation process can change. Dedicated metrics quantify how well the design, i.e. the set of design parameter values, satisfies the design objectives, such as thermal, stress, and lifing objectives, which are analysed

with proprietary and COTS tools. Lifing is predicting the expected lifetime of a component or assembly for loads resulting from the designed use. These metrics are similar to the "mission analysis" process of the wing case in Figure 5. The partly automated optimisation process modifies the parameters to obtain an optimal design with respect to the chosen objectives. The result from an optimisation loop has to be processed in such a way that it can be fed back into the Product Data Management (PDM) and in the CAD design systems.
Furthermore advanced multidisciplinary design and optimisation technology is needed for the automation of meshing and the automated inclusion of boundary conditions in the analysis. Meshing is a mathematical procedure to select the discrete points in the continuous mathematical multidimensional space for which the equations are calculated which provide the basis for the subsequent optimisation processes.

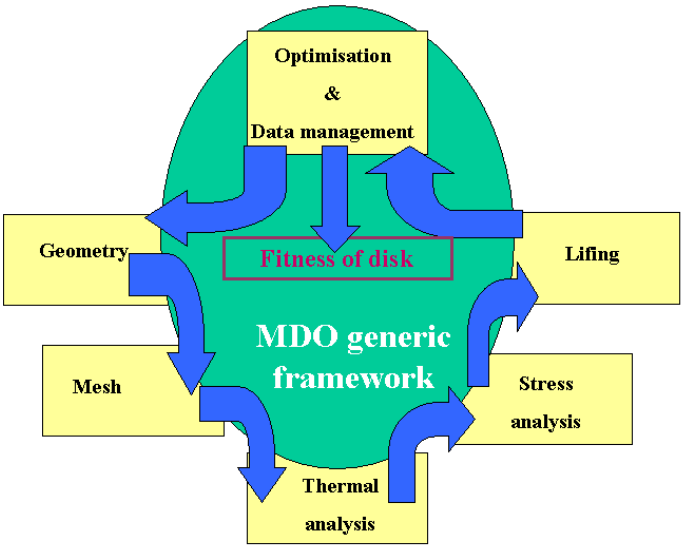

Figure 6 Thermo-mechanical engine disc design and optimisation process

Another challenge is the set-up of an integrated analysis and optimisation process in such a way that non-experts can run it and understand the results whereas single-discipline experts can still intervene and customise the design and optimisation processes to their needs. This is depicted in Figure 6, where the "fitness of disk" is the metric to be optimised (similar to the range used in Figure 5). In this way the engine MDO capability contributes to the knowledge management for the partners involved. The partner's first iteration results do provide user value for the partners involved. More information on the engine MDO case is contained in[19] and [20].

5.2 Two-component engine multidisciplinary design optimisation

In the second iteration, the high-pressure turbine disc analysis and optimisation will be extended with the analysis and optimisation of an additional component. In the multidisciplinary analysis and optimisation taxonomy as presented in Figure 2, full multidisciplinary analysis and optimisation is achieved. Through this multi-level optimisation three challenges are addressed:

- the interaction between the engine components means that the optimal whole engine design is unlikely to be composed of the components that have been "locally" optimised on the basis of single suppliers' needs only;
- model fidelity and computational speed for a whole engine analysis and optimisation are contradictory;
- the potential number of design parameters in the optimisation is very large.

The second iteration will be run on local sites, each of which uses the partner's own tool chain or workflow. Additionally one partner integrated a data sharing facility to its MDO tool chain. This will allow geographically dispersed multi-partner MDO to be run in a subsequent iteration.

6 Geographicly dispersed co-operation

It has been observed that 60% of the value of modern aircraft is provided by suppliers[3]. One of the objectives is to reduce the time-to-market, so the coordination between the various design tasks needs to be improved. In order to better understand coordination, the often-referenced definition from[21] is used: coordination is managing dependencies between activities.
From the observation that information technology (IT) tools can improve coordination,[21] three effects can be predicted. The first order effect will be that IT supported coordination will replace human coordination. The second order effect will be that coordination will increase as it becomes more affordable. The third order effect will be that the increased communication opportunities will change the organisation. In some highly competitive industries, like consumer electronics or personal computers, such changes have already occurred. Table 1 provides an overview of different types of resource allocation. To increase design process efficiency, providing more affordable coordination allows choosing from a larger set of resource allocation mechanisms to select the most suitable one. Table 1 indicates the increasing options when moving from a traditional hierarchical organisation, via a networked organisation to market-based collaboration.

Table 1 Different mechanisms for resource allocation, from[22]

Step	**Hierarchy**	**Network**	**Market**
Identify needs	Based on specializations in firm	Based on specializations in network	Based on specializations in market
Identify resources	Use known set of resources in firm	Use known set of resources belonging to network	Broadcast a RFP and wait for replies, check advertising
Choose resource	Specialization, workload	Specialization	Evaluate bids
Assign resource	Employment relation	Network membership	Contract

Classification of coordination and possible resource allocation mechanisms serves as inspiration for change. The approach taken by the first case study discussed in this paper is to make coordination between tools available and affordable to facilitate knowledge management, resulting in the wing MDO capability. Subsequently new design strategies can materialise, like automated Multidisciplinary Design and Optimisation (MDO) or response surface based optimisation, aiming at the third order effect on aircraft design. The resulting MDO capabilities are a form of knowledge management to retain such knowledge for re-use.
Within collaborative aircraft development projects, analysis capabilities, such as for the described wing and engine case, need to be shared or distributed across programme partners of the networked organisation (see table 1). However, there may be strict limitations in the distribution or exchange of tools (commercial or in-house developed) among the networked partners because of computing platform requirements, licensing aspects, and Intellectual Property Rights (IPR) restrictions. Sharing such analysis capabilities within collaborative aircraft development partners therefore requires a distributed solution that allows for flexible configuration of the analysis process and supports convenient access for discipline expert users which are not necessarily IT-experts. Also the discipline experts need only to have access to standard desktop systems and may not be required to have access to the dedicated computational equipment needed by some models.
For the wing case, Figure 7 below illustrates the process of operating the geographically distributed wing MDO capability. The discipline expert (i.e. the designer) initiates the design process by specifying the design (e.g. wing geometry parameters) in the Integrated Design Model (one of the key collaborative engineering elements[14] discussed in chapter 3). In this wing MDO case the IDM is a text file where all relevant input and output data of the design processes is stored. This IDM (i.e. the file) is selected by the discipline expert, possibly modified and uploaded to the wing MDO via a web service. The web service takes care that the IDM is properly submitted and the wing analysis process is initiated. First the “geometry generation” process executed, in which consistent geometric models of the aircraft wing and fuselage for the structural optimisation and cruise aerodynamic analyses are generated, see Figure 5 and section 4.2. Upon completion, selected results (in this case the resulting geometric parameters stored in the IDM and a graphic representation of the geometric aerodynamic model) are returned to the discipline expert via the web service. These results of the first wing MDO process can be inspected by the discipline experts on their standard desktop computers. If the discipline expert is satisfied with the results, the IDM is submitted again to the wing MDO via the web service, as illustrated by the dotted lines in Figure 7. The remaining analyses of the full wing MDO analysis process will now be executed, upon completion returning selected results to the discipline expert. It should be noted that the remaining process could similarly have been executed at a partner’s site without any difference noticeable to the discipline expert. For example, if the next step “Engine Sizing” would require a specific tool available at the engine manufacturer’s site, this could have been performed similarly to the geometry generation process described above. Key aspects here would be that all relevant data is exchanged via the

IDM, and that the web service offered by the engine manufacturer (via their web access page) would be accessible by the discipline expert.

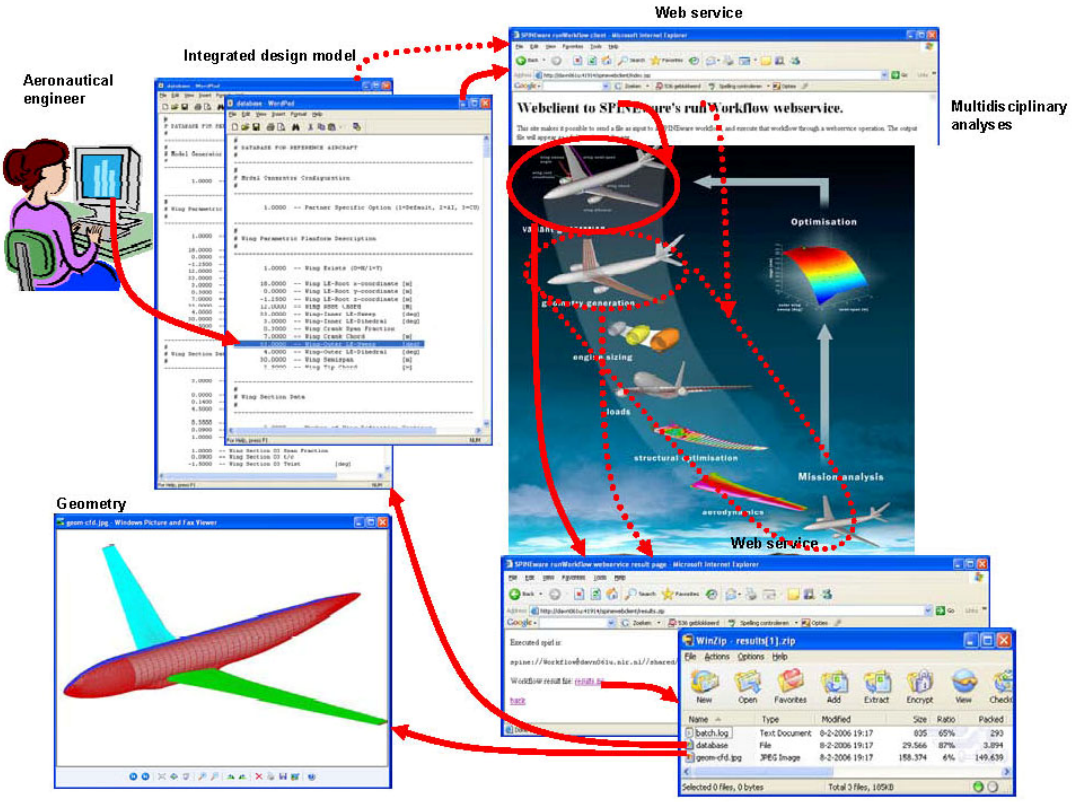

Figure 7 Illustration of the geographically distributed wing design process

7 Conclusions

There is eminent commercial and technical value in improved knowledge on the characteristics of aircraft or engine in their early design phases. Multidisciplinary design optimisation is a way to improve that knowledge as well as to augment the performance of the resulting design. For the two cases addressed in this paper, aircraft wing and engine, the obtained MDO results demonstrate these benefits. With these achievements the current MDO state-of-the-art is further advanced.

The MDO capabilities capture the knowledge of the various discipline experts involved and make these accessible to others, i.e. perform knowledge management and knowledge based engineering.

While realising the MDO capabilities the evolutionary approach is used, as opposed to the waterfall approach traditionally used in the aerospace domain. Already after two iterations, this approach has demonstrated to be feasible and beneficial.

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