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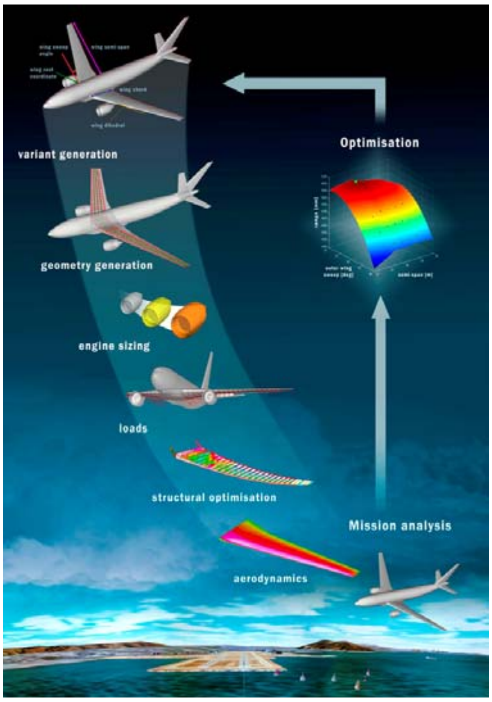
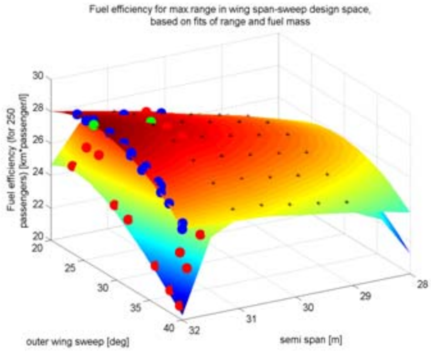
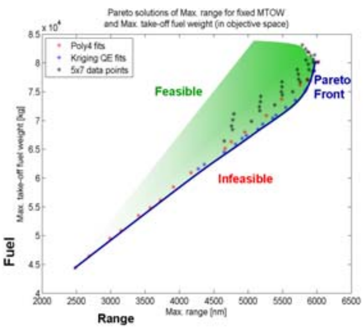
Executive summary

Multidisciplinary design analysis and multi-objective optimisation applied to aircraft wing







Multidisciplinary design analysis capability (left), response surfaces for one selected objective (fuel efficiency) in the selected design space (top right) and Pareto optimal designs for two selected objectives (fuel, range) in the same design space (bottom right).

Problem description
The design of complex high-tech systems, like aircraft wings, typically requires simulations of the system by multiple disciplinary analyses based on a consistent design description. Such simulations yield various characteristics of the system. The multidisciplinary team needs support to efficiently evaluate the many possible designs to arrive at an optimum design. During the optimisation, increasing knowledge of the behaviour of the design leads to an evolution of the design objective. The multidisciplinary team benefits from the support for this process.

Description of work
First an integrated wing design analysis capability has been realised. This capability uses an

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integrated design model to consistently exchange design information between the disciplines involved. For the wing-design case study the disciplines involved include geometry generation, engine sizing, structural optimisation and aerodynamics.

Subsequently a computationally efficient capability has been developed to fit response surfaces through resulting design characteristics for the analysed design space. The last part of the work is to apply different optimisation algorithms to this response surface to obtain the best performing design with respect to the objectives chosen.

Results and conclusions
An initial multidisciplinary design analysis capability has been realised for wing design. This capability is sufficiently robust to explore the design space. For this case study a Matlab-based software system to generate response surfaces performed efficiently. Various optimisation algorithms provided similar optima. Verification with the full analysis capability confirmed the optimum design values.

As the definition of the design objective for such complex designs is not obvious, the combination of the integrated design model, efficient response surface modelling and a choice of optimisation algorithms supported the design team in obtaining knowledge of the behaviour of the design.

Applicability
Embedding proprietary and COTS design tools into a multidisciplinary wing design workflow demonstrates NLR tool integration capabilities.

Fitting response surfaces through flexibly selected design space results, allows for efficient approximation of computationally expense analysis and effectively supports the design team.

Together these facilities can improve engineering processes in aerospace industry for complex designs beyond aircraft wing.

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Multidisciplinary design analysis and multi-objective optimisation applied to aircraft wing

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Summary

Design of complex high-tech systems typically requires an integrated analysis of the multiple interacting physical phenomena that jointly influence the overall system's behaviour. For aircraft wings, for example, the aerodynamic loading and the wing structural deformation strongly interact, with their balance determining the overall wing behaviour. This balance must be evaluated for the different operational conditions the wing is exposed to, such as the cruise, manoeuvre, or take-off conditions. In addition, various objectives and constraints, based on for example, drag, lift, weight, range, or fuel consumption, must be taken into account when designing aircraft wings. The choice depends on the key design goals being addressed. This requires high flexibility in the selection of the results of the integrated design analysis to adequately formulate the appropriate (constrained) optimisation problem representing the considered design case. The current work presents a flexible approach for multidisciplinary design analysis and optimisation, and its application to aircraft wing design. The achieved results show significant improvements of the wing performance for different design goals, demonstrating the effectiveness and flexibility of the proposed approach.

Contents

Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
CFD	Computational Fluid Dynamics
FAR	(US) Federal Aviation Regulation
FEM	Finite Elements Methods
IDM	Integrated Design Model
JAR	(European) Joint Aviation Requirements
MDO	Multidisciplinary Design Optimisation

1 Introduction

For designing high-tech products like aircraft, simulation is of key importance. World-wide competition in 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 up to the year 2020. This vision mentions advanced, integrated and collaborative analysis and design capabilities as key enablers. Industry confirms a multidisciplinary approach being instrumental for achieving improved designs [2], [3].

This report describes an advanced and integrated approach for collaborative multidisciplinary design combining consistent multidisciplinary analysis with multi objective optimisation. Aircraft wing design is considered a suitable case to illustrate the concepts and to present the results obtained.

The next section elaborates upon multidisciplinary design optimisation and its relevance for early design phases before explaining the analysis implemented and optimisation approach. In order to illustrate the fidelity of the models used in this study, some additional detail of the structural optimisation is provided. To illustrate the benefits of multi objective optimisation selected results are provided. The last section describes the future work enabling the collaborative enterprise before presenting the conclusions.

2 Multidisciplinary design and optimisation

NASA [4] defines multidisciplinary design and optimisation (MDO) as a methodology for the design of complex engineering systems and subsystems that coherently exploits the synergy of mutually interacting phenomena. The American Institute of Aeronautics and Astronautics (AIAA) [5] more informal definition is "how to decide what to change, and to what extent to change it, when everything influences everything else". This succinctly holds for the objectives of the wing case study, as wing design is an inherently multidisciplinary activity including analyses in disciplines like aerodynamics, structures, flight control, manufacturing, etc.

For complex 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 of the life-cycle cost, the wing design case study presented pertains to the early phases of aircraft design. Traditionally semi-empirical rules are relied on in early design. 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 reductions in cost, depicted in Fig. 1, or time-to-market are important.

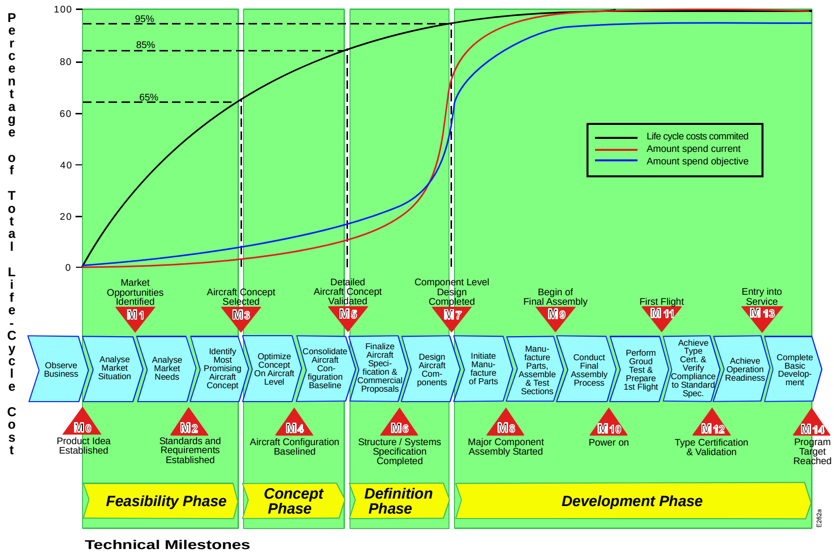

Fig. 1 Relative amount of costs fixed and spend during life-cycle based on aircraft data from [6] and general domain information from [7]

At system level, traditionally the knowledge and experience of the human designers involved are 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 as follows. The aerodynamics expert designs a wing surface using dedicated computer-based models and tools. Relevant aerodynamic forces are calculated and 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 formulated 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 [4]”. The work presented aims to couple the key disciplines involved in the aircraft wing design process by integrating the dedicated design tools used. Next, a suitable optimisation algorithm is coupled to efficiently explore the wing design space to arrive at an optimum with respect to the defined objectives.

As objectives typically evolve during the life-cycle, it is important that the designers are provided with insight into the design space. The work presented aims to support a designer with this.

For a single wing optimisation, it is expected that the multidisciplinary analysis capability 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.

3 Multidisciplinary wing analysis capability

Figure 2 depicts the top-level view of the wing multidisciplinary analysis capability. The wing optimisation is based on a multi-level optimisation; i.e. in addition to the top-level full-wing analysis and optimisation as shown in Fig. 2, some lower-level analyses processes include optimisation processes at their own level. For example the engine-sizing process optimises the thermodynamic cycles to arrive at minimum fuel consumption and hence also minimum emissions. The major top-level components illustrated in Fig. 2 are succinctly described below.

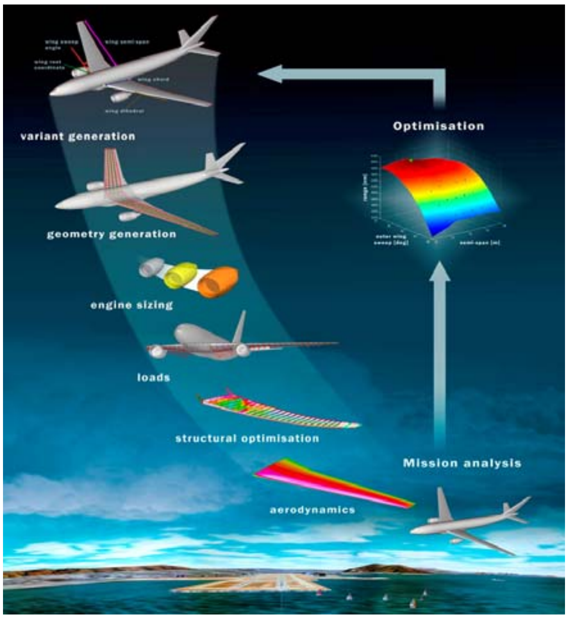

Fig. 2 Overview of the multidisciplinary wing analysis capability

The *variant generation* component uses a number of parameters to define the 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* a scalable engine data set is being used to determine the engine weight and the corresponding fuel flow for the required take-off thrust. This is also referred to as a “rubberised engine” model. If more engine characteristics are required, the engine sizing component can be replaced by more detailed simulation like GSP [10], illustrating the adaptability of the MDO capability.

The *structural optimisation* component determines the optimised 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 a Computational Fluid Dynamics (CFD) full-potential boundary layer simulation of the wing in 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.

The last major component is *mission analysis*. This component calculates various key aircraft mission characteristics for 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 components exchange their data via an Integrated Design Model (IDM, depicted in the right part of Fig. 3), 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 [11] or its European Joint Aviation Requirements (JAR 25) equivalent should be considered. However, in order to simplify the analyses and to comply with the strict computing time demands as stated in section 2 above, only a single representative load case is analysed, consisting of a +2.5 *g* pull-up manoeuvre. Moreover, this load case is configured such that the wing structure experiences maximum bending moments, i.e. maximum payload and full fuselage tank.

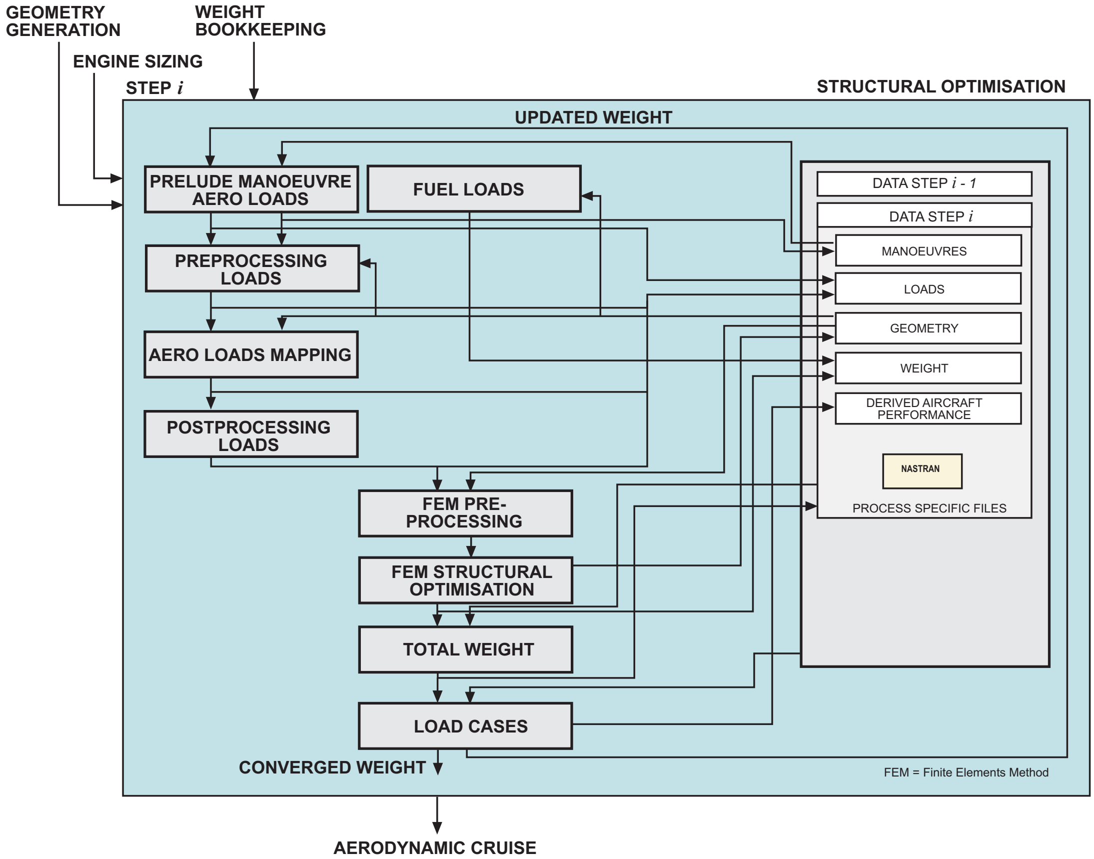

Fig. 3 Details of structural optimisation process

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. A local 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.

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 [12]. 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 to the structural grid points.

The wing structural layout is provided by the *geometry generation* module via the integrated design model. For engines, data including weight and thrust forces from the engine-sizing module are obtained via the integrated design model.

The structural analysis uses FEM tool MSC-NASTRAN. Some results of the optimised wing structure are given in Fig. 5 below.

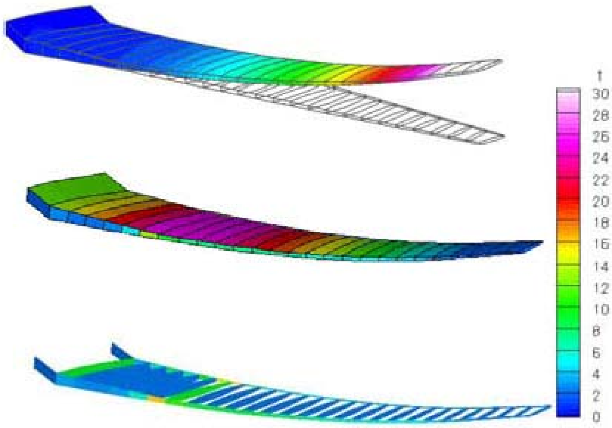

Fig. 5 Top: Maximum wing deformation at +2.5 g manoeuvre. Wing thickness optimisation results at +2.5 g manoeuvre for wing thickness (middle) and internal structures (bottom).

Where the engine weight and thrust forces are transferred, a thicker rib and adjacent beam sections (in the inner wing) result. 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 +2.5g manoeuvre analysed. More information on the wing optimisation is provided in [13].

5 Multi objective wing design optimisation

The multidisciplinary design analysis capability described in the previous sections typically takes of the order of one half hour to perform a full sequential analysis of a single wing design. The computational fluid dynamics analysis consumes most time even when executed on a dedicated computer, allowing running of all other analyses in parallel.

To efficiently determine the best wing design, advanced numerical optimisation algorithms can be deployed. For such complex, possibly high-dimensional and non-linear constrained design optimisation problems, these optimisation algorithms need to evaluate many different wing design variants. The high computational costs of the many resulting wing analyses favour a meta-modelling approach in order to accelerate this optimisation. In such an approach the wing designer determines the relevant part of the design space for the wing design parameters involved. This design space is sampled with a relatively low number of design points for which the full multidisciplinary wing analysis is performed. A meta-model of the data is obtained for this design space by fitting a suitable approximation function for each selected characteristic through the design points. Note that as the full Integrated Design Model is available for each wing design point, any stored characteristic can be selected.

As an example, a wing design case study has been performed considering a design space spanned by only two of the wing design parameters: the wing semi-span, and the outer wing sweep angle. As initial design goal, maximising the range intuitively seems an appropriate objective for the wing design.

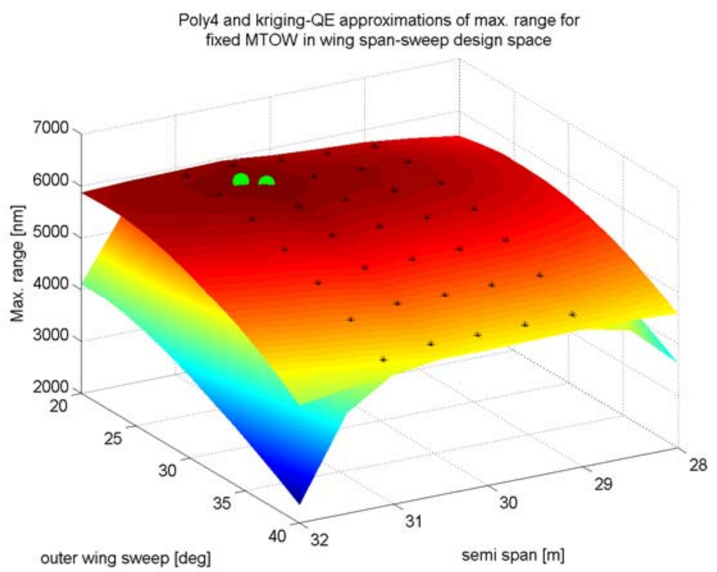

Fig. 6 Response surface for range as objective function for two design variables (wing sweep, wing semi span), two fitting functions (Kriging, 4th order polynomial), the reference wing (grey) and optimum wing design points (green) found

Fig. 6 illustrates the original data (black points) and the meta-model for the calculated range. Various fit functions have been used. Those yielding the most accurate fits (Kriging quadratic exponential and 4th order polynomial) are shown in Fig 6. More info on the fitting tool used can be found in [14], [15]. To find the optimum range values as predicted by the resulting two fits (or response surfaces), various optimisation algorithms have been used. All algorithms find the same optimum design points for the two fits. These results are also indicated in Fig. 6. Subsequently the optimal design point predicted by the 4th order polynomial has been verified by evaluation with the full analysis capability. A substantial range improvement of 10% can be obtained with respect to the reference wing (Fig. 6). Moreover, the computational efficiency of the complete optimisation was quite high, considering that the determination of the meta-models as well as their optimisations required only a few seconds computational time on a standard desktop PC.

Using the data from the integrated design model, maximising the range implies adding more fuel, impacting operating costs and the environment. Illustrating how the combination of the integrated design model and optimiser allows support for the designers, fuel consumption is now selected as an alternative objective, and treated similarly as the range. Fig. 7 provides the resulting response surfaces and design optima for fuel consumption. As this result is obtained at the edge of the design space, the accuracy of the meta-model prediction is likely to be low, as confirmed by the relatively large difference in predicted values by the two different fits. Nevertheless, these examples illustrate the typical case that defining a good objective can be non-trivial for a team of co-operating designers. As the optimisation problem can be quickly reformulated and computed, designers can afford to explore more objectives.

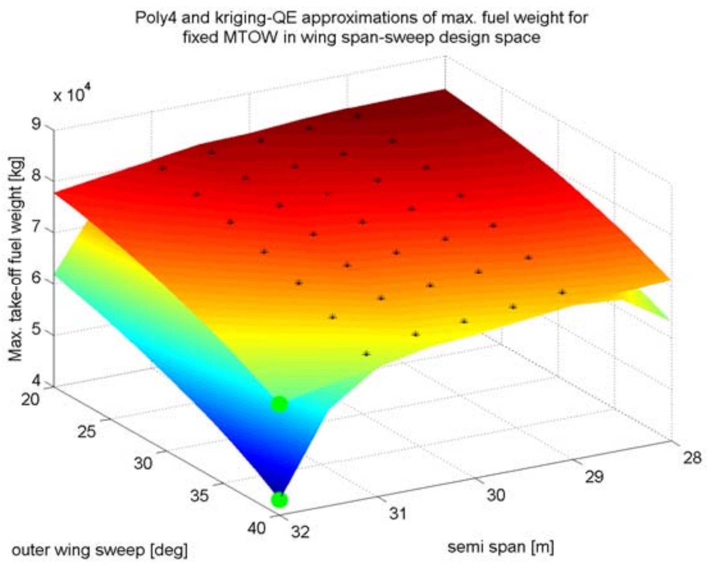

Fig. 7 Response surface for fuel as objective function for wing design space

Figure 7 also shows that minimising fuel consumption results in a very low range. Therefore in this case maximising the fuel efficiency is probably a more suitable design objective.

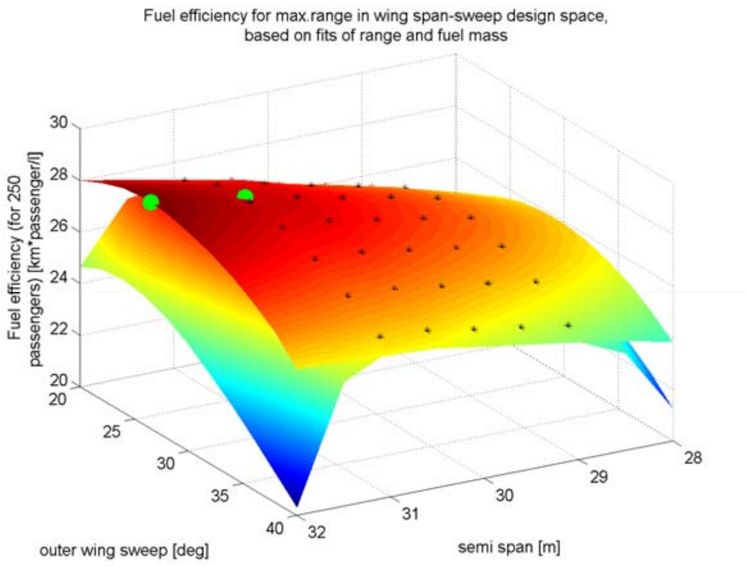

Fig. 8 Response surface for fuel efficiency as objective function for wing design space

To facilitate comparison of the aircraft's fuel efficiency with other means of transport, the fuel efficiency results in Fig. 8 are expressed in passenger kilometres per litre, for the 250 passenger aircraft design. The resulting optimum design combines a 7% range improvement with a 4% increased fuel efficiency and consequently reduced environmental impact. Both improvements are significant.

The drawback of maximising fuel efficiency is that the resulting design is only valid for a fixed range, i.e. 5721 nautical miles (nm). As multidisciplinary design optimisation is intended to support designers to improve their understanding of the design for the defined design space, multi objective optimisation is a suitable approach for retaining more flexibility in design choices. To give an example, in this case the range and fuel objectives are selected to be simultaneously maximised and minimised, respectively. The best designs are those where further improving one objective will reduce the other objective, i.e. designs on the so called Pareto front [16]. To determine this Pareto front a multi-objective genetic algorithm is used. Determining the Pareto front by this algorithm with the depicted number of design points takes in the order of 10 seconds, which is computationally affordable and its computational requirements are negligible compared with even only a single wing design analysis. More detail on the specific algorithm used is contained in [15]. As can be seen in the top right part of Fig. 9, 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.

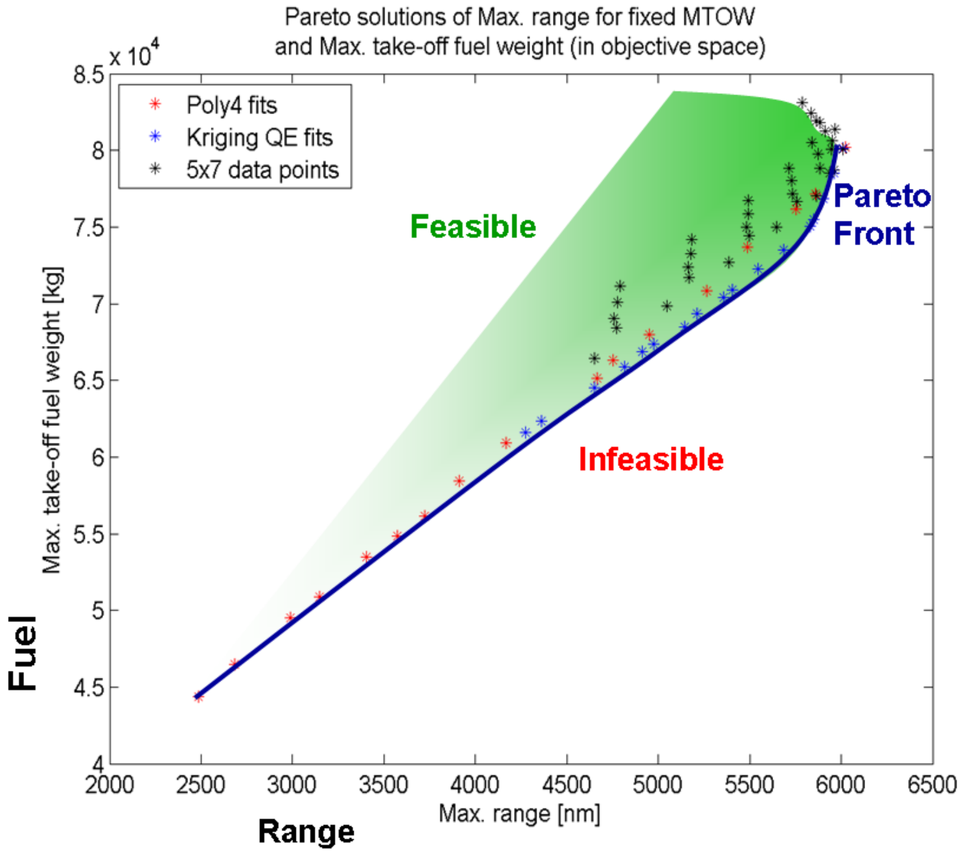

Fig. 9 Original wing designs (blue) with respect to both design objectives (range, Maximum take Off Fuel Weight) and the obtained Pareto front

The Pareto front provides information on the sensitivity of a design with respect to the selected objectives. Fig. 10 shows the wing designs depicted in design parameter space, which correspond to the Pareto front points in Fig. 9. In this case many of the Pareto designs favour a single value of one objective (semi span) but vary in the other objective (sweep angle).

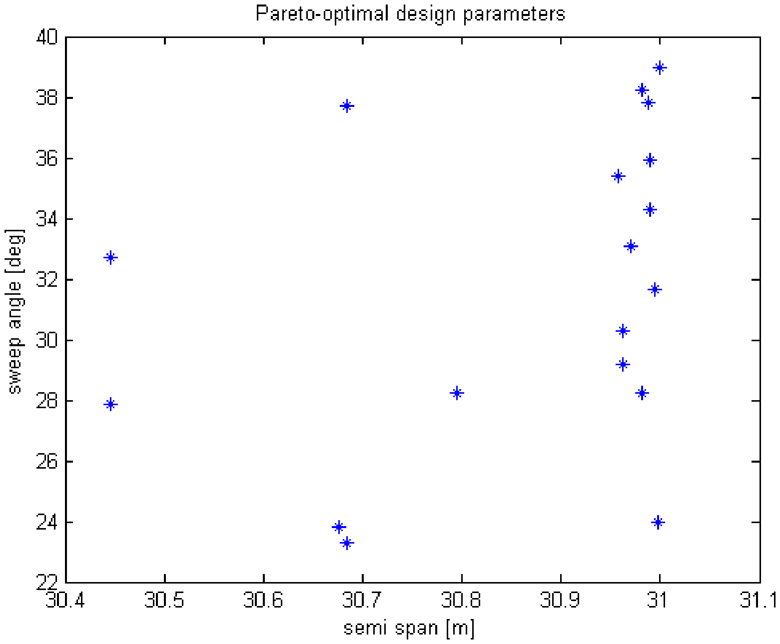

Fig. 10 Wing designs forming the Pareto front depicted in Fig. 9 in design space

The Pareto front presented also allows for range choice, for instance 4500 nm, and determination of the corresponding “minimal fuel” optimal wing design. Fig. 11 depicts the Pareto design points for one objective with the resulting design parameters. The resulting fuel efficiency obtained from the integrated design model is somewhat disappointing, which could be caused by other assumptions of the wing analysis, like the selected cruise speed which is not optimal for the wing design or a fixed payload (i.e. number of passengers) which could be improved for the wing design. Further analysis could be performed by defining a new design space around such wing design, illustrating how multidisciplinary design analysis can be used to guide the design process.

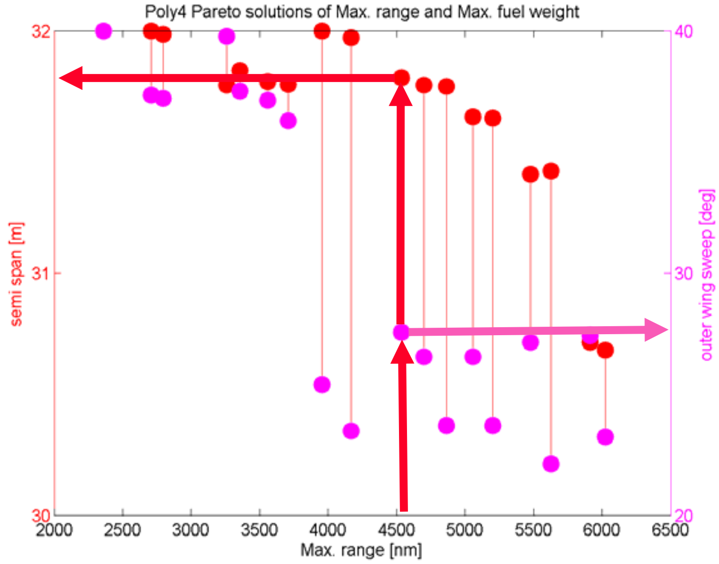

Fig. 11 One objective of the wing designs forming the Pareto front depicted in Fig. 9 related to both parameters of the wing design space

Table 1 summarises the different designs obtained using different objectives. It shows that different objectives lead to different designs having significantly different properties. This illustrates the power of multidisciplinary analysis tools combined with advanced meta modelling methods and (multi objective) optimisers for a group of expert designers. It also shows that such a tool suite does not offer an alternative to expert knowledge. A suitable initial design has to be selected. Also, in the case of many design parameters, say more then three, it is difficult to extract meaning from the Pareto results. Consequently the designers need to carefully define a suitable design space, and carefully interpret the results taking the assumptions underlying the analysis well into account. The results confirm the statements of the aircraft manufacturers in [2] and [3] of the added value these multidisciplinary and multi-objective tools bring to the resulting design.

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

	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
Selected Pareto point	31,80	27,5	4 535	63 768	26,3

6 Conclusions

Competitive pressure from an open world-wide market enforces the need for permanent improvement of complex high-tech products. Aircraft are no exception. In these products most costs are determined in the early design phases [6], [7]. Emerging simulation capabilities, with increasing fidelity of the major design disciplines, offer the potential for multidisciplinary design optimisation. For an aircraft wing design, a multidisciplinary analysis capability based on an integrated design model has been realised. Subsequently single objective and multi-objective optimisation for the design has been demonstrated. The results obtained achieved significant improvement of the design, confirming the industry view of the importance of multidisciplinary design optimisation to improve their designs [2], [3] to accommodate market needs.

7 Discussion: embedding the design capability in the collaborative enterprise

For high-tech complex products produced for competitive markets, suppliers provide a significant part of the product value. The prime contractor acts as system integrator, closely cooperating with a selected number of the risk sharing first tier suppliers complemented by many more lower tier suppliers. With 60% supplier content, aircraft are no exception [17]. The resulting close collaboration between various partners during the design phases requires design capabilities like the wing MDO to be available to all partners of the networked collaborative enterprise. Due to the risk sharing nature of the collaboration, partners prefer to use their own tool suite at their own premises. However partners need to benefit from access to the integrated design model and the full precision tools of the other partners for assessing the consequences of their own design decisions. The result complies with the definition of a collaborative enterprise which uses shared re-usable business models on an enterprise wide scale [18].

Distributing the integrated design capability amongst all partners is impeded by limitations on (commercial or proprietary) tools. Such limitations include variation in computing platforms, Intellectual Property Rights and increasingly tight security policies of the partners involved. Future work is planned for flexibly combining partners' assets into a shared capability with convenient access for all design experts concerned both at their local offices and for the duration of the collaboration. Usually the designers are not information technology experts, implying the need for solutions which are simple to operate and robust. Initial experience suggests service oriented architecture to be a promising candidate solution.

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