

THE NEW MDO FRONTIER, THE MULTIDISCIPLINARY DESIGN ORGANIZATION CHALLENGE

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Keywords: *multi-disciplinary design, MDO*

Abstract

One of the major challenges of MDO is its actual implementation in the industrial context. In practice, the introduction of an MDO strategy must take into account the existing organizations and processes. Surrogate models can help circumvent some difficulties since they can be easily constructed using the existing process and organizations. Furthermore the surrogate models facilitate the extensive exploration of the design space and allow interactive visualization features. The interactive visualization is an important tool that not only helps in understanding the potential solutions but also permits to involve the different design teams by showing them the impact of the local decisions on the global design.

The method is described and some tools are detailed. A trade off example is then presented.

1 Introduction

Multidisciplinary Optimization or MDO is an extensively studied field. Several optimization strategies now exist and can be used on a fairly large scale as demonstrated in the European Research Project HISAC¹. The next logical step is to incorporate the MDO methodology in the decision making process of the design of an actual product and lies ahead of us the organizational challenge. In this paper we

propose some directions and identify the major hurdles to be overcome.

The design of complex systems today follows a capability based approach. This is to solve the inverse problem: for a given set of requirements (e.g. performances, cost, ...), which is the system that meets them? The solution of this inverse problem can then select the system and its architecture in terms of overall capabilities. In this approach it is necessary to establish a link between the requirements representing the expected performance of the system and the design parameters. This parametric approach allows the simultaneous convergence of *both the requirements and the design* of the system.

Decisions taken at the beginning of a project play an important role towards the success of the project. There is a real challenge to provide assistance to decision makers enabling them to better manage the multiple criteria, often conflicting, and the uncertainties always associated with decision making in complex systems design. It is necessary, from the most upstream phases of the project, to understand how requirements interact, what are their impacts on the design, what are the options and their associated probability of success...

The numerical simulation used in an appropriate environment can support decisions by enabling the decision makers to explore the behaviour of the system for different scenarios since the inception of the project. Up to now, MDO processes were apprehended under the "simulate to optimize" aspect, the current effort is positioned in "the synthesize to decide" aspect.

¹ A research integrated project supported by the European Commission under the Sixth Framework and addressing Research Area 2 "Improving environmental impact with regard to emissions and noise", of Thematic Priority 1.4 Aeronautics & Space Contract n° AIP4-CT-2005-516132

2. Decision process in design

The process leading to the selection of a good solution meeting all the requirements can be decomposed into the following steps:

- Definition of the problem : the high level requirements are translated in objectives and constraints
- Definition of the design space: technologies and architectures best suited to meet the objectives are chosen as well as the design variables
- Models and simulations: the level of fidelity of the required simulation are chosen and the simulations are performed, surrogate models are constructed
- Exploration of the design space: the surrogate models are used to extensively explore the design space and evaluate the trade offs.
- Synthesize the information: interactive visualization tools are used to analyze the solutions, to understand the impact of the requirements, to identify where gains should be obtained

The decision process in design can be represented schematically as shown in figure 1.

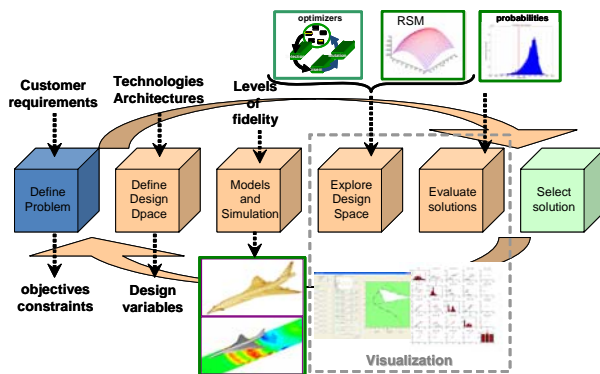


Fig. 1 Decision loop in design

The loop is repeated several times during the design process since the conceptual design step that allows consolidating a sound set of requirement in assessing their various impacts, and throughout the preliminary design when the design parameters are optimally sized to meet the requirements.

3 The Challenges

The challenge is to establish the sound foundations for a complete collaborative environment to support decisions in the most iterative periods of the design process. It is during the early phases, from the concept maturation to the preliminary design review, that the efficient use of simulation tools is the most strategic. This is the time when it is necessary to systematically explore all the important parameters and understand their interactions (whether they are design parameters or requirements) to ensure the best possible solution, when uncertainties are to be quantified to manage margins in a rational manner and when results need to be synthesized and presented in a clear and interactive manner to the decisions makers.

The ambition is to immerse the decision makers in the decision space or more accurately within the space of compromise in order to enable them to better understand what they need by providing them immediate answers to their questions. It is necessary to realize this in a collaborative mode to ensure that all stakeholders can measure the impact of multiple interactions and be able to trace the analysis at the system level. To efficiently manage the trade off between breadth and depth this methodology must be used in an iterative process, each compromise decided at the system level allows focusing future efforts on smaller areas but with an increase in the depth of details.

4 Multi-Level MDO at Dassault-Aviation

The design of a complex system, for example an aircraft, is conducted in a hierarchical manner from the global definition to the details of the components. This organization is represented today by a tree of digital models. At each level and for each discipline there are two types of coupled models:

- A model definition describing the product (e.g. the CAD model for the geometry)
- Models used in the calculations or test articles, to demonstrate the product

meets its specifications or follows the rules of the art.

Figure 2 presents the multi level MDO process in use today at Dassault-Aviation [1].

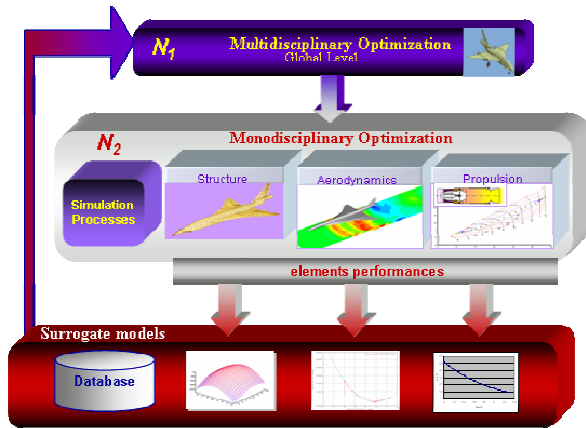


Fig. 2 Schematic of a Multi Level MDO process

This is essentially a two level process that is organized as follows:

- The N_1 level is the global level which identifies and manages the important global parameters, performs the optimization at the global level and select the optimal designs.
- The N_2 level is the level of the detailed analysis. At this level, each discipline identifies its important private design parameters (if a parameter is shared by several disciplines it either managed at the global level or directly at the detailed level by one discipline), manage its own compromises, select the technologies, select the designs and generate the local models.

The database is primarily composed of surrogate models (e.g. response surfaces) which are generated by each discipline and are used for the global optimization.

The extensive use of this process during the HISAC project highlighted some weaknesses. This process relies heavily on local optimizations for which it is difficult to specify the correct objective function. To overcome that the obvious solution would be to construct a global model with which the MDO would be performed. Unfortunately, it is not possible today to model in a homogeneous manner a

complex system such as an entire aircraft. Furthermore, beyond the limits of the tools, the coupling of all the models at all levels would not be effective in practice. The various disciplines involved are not progressing at the same pace and do not necessarily need access to all information. A fully coupled approach would already be difficult to implement in an entity geographically located on one site, not to mention the difficulties of communication if different actors are geographically dispersed or if external collaborations are needed. Finally, in such an automatic approach the place of the human is not clear, while its role as a decision-maker asked him to be immersed in the heart of the trade off analysis. We therefore feel confident that this multi level approach is sound and worth being improved.

The three major improvements sought concern:

- The systematic generation and management of surrogates models within a true database to allow their use in any context (be it reduction between detailed to global level, exchange of information at the local level or projection from the global level to the detailed level)
- The extension of this methodology beyond the physical modelling
- The interactive presentation of the potential solution, and their associated uncertainties, to decision makers.

Progress in these fields will allow MDO to be the corner stone of a decision process supported by a global methodology described below.

5 The Multidisciplinary Design Organization

The approach proposed reinstalls the man in the loop and is illustrated below by a representation of the necessary functional groups. The general idea is to have simulation processes, multi-physical and systemic, feeding a database used to support simulations at the system level post-processed with interactive visualization tools used to identify the aim of the new analysis.

Each individual component (global monitor, simulation process, data container,

visualization) presents different challenges depending on the nature and the maturity of existing tools. The interaction between the groups must also be studied specifically for the development of an overall process used industrially.

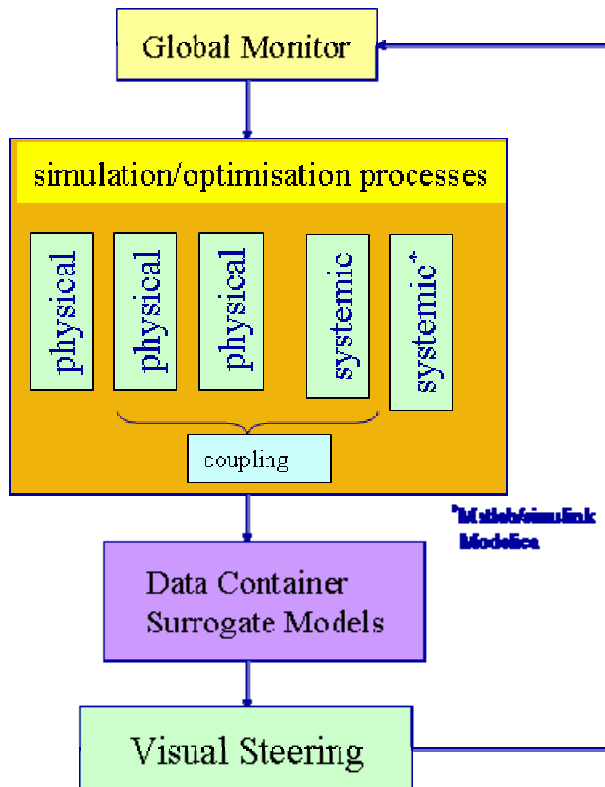


Fig. 3 Multi Disciplinary Design Functional Groups

The *simulation processes* have long been studied and solutions, either commercial or in-house, exist, particularly for physical simulations. The step forward in this area is the introduction of "systemic" simulations (typically based on Matlab / Simulink, Scilab / Scicos Modelica simulations to fix the ideas), and to interface them with the physical simulations. The eventual objective is to have a platform host of different models (0D to 3D) allowing the easy assembly of a system from libraries of components. The collaborative aspect and the distribution of computer equipment need also be taken into account. Here the automation aims at enabling the "What if analysis" by answering questions in a timely manner. The major challenge lies in the ease of the reconfiguration of the assembly of models. We prefer to have the minimal set of models tailored to answer specific questions rapidly instead of

constructing a fixed model that could answer (almost) all questions but at the expense of the efficiency.

The *data container* is to enable the sharing of geometric or systemic definitions, ensure the consistency of boundary conditions and the consistency of the system models by proposing a set of data models. These models, crucial for the parametric analysis that we seek, must handle both the relevant parameters and results of detailed simulations and contain their domain of validity, their accuracy and the uncertainties.

The *visual steering* contains the Man Data Interface. The MDI, through the implementation of optimizers and post-processing using statistical models, will identify the key parameters, the overall exchange rates, and the areas of analysis to be refined for a maximum ROI whether to improve the performances or to define designs reducing the uncertainties. The MDI is central in providing insight to decision makers.

The *global monitor* is to organize and manage the detailed analysis, define the local optimizations and sensitivity analysis necessary to meet a specified confidence level for the results of simulations. The level of automation of the component is yet to be defined but it is crucial that the monitoring is performed by the dedicated design teams. At least for a while, this step can be done manually, each team using their own simulation processes which are more and more automatic.

6 The process implementation Challenges

The data container and the visual steering represent the major challenges.

For the data container, among the issues one have to find a clever manner to manage data from different sources (e.g. tests or computations), build and manage a hierarchy of models, equipped these models with domain of validity, uncertainties,... The interoperability of the models must be guaranteed either through real standards or de-facto standards, the question of the reuse of these models to capitalize on previous studies must be addressed and of course the models should be able to protect the intellectual property in the case of

project in cooperation. During decision reviews, the analysis of the space of compromise by decision makers often drive them to ask specific technical questions related to the global performances of the aircraft. To get answers to such questions, dedicated studies may have to be conducted by one or several disciplines. It is of great importance to trace such a process, keeping alive the link between the question(s), the answer(s) and the process(es) (computations, tests, engineers know-how,...) that allowed to get the answer(s). This is a key function that enables an efficient reuse of past experiences and experts know-how. Furthermore this database needs to be user friendly and well adapted to the project undertaken.

For the visual steering, the only example that we are aware of is the Collaborative Visualization Environment of the Aerospace Design Lab of the Georgia Institute of Technology [2]. This realisation will serve as a guideline but some questions remain open such as how to intuitively visualize uncertainties, how to calculate on the fly the level of confidence to an answer using the pre computed database, how to efficiently benefit from the ever growing computer speed to compute on the fly...

We believe that this integrated process is crucial to convince the different design teams to adopt a true Multi Disciplinary Optimization approach in their daily Multidisciplinary Design. The key element will be that each team will *individually* benefit from this process that will allow them to *see* the overall impact of their local design choices, and will lead to a *collective* acceptance of the compromises and open the right design parameters to be creatively exploited.

7 Interactive visualization

A tool dedicated to the interactive visualization is being developed in Matlab. Matlab provides a programming environment for the development of Graphic User Interfaces and advanced mathematical treatments can be easily implemented. The two main features

discussed here are the sensitivity analysis and the interactive visualisation.

7.1 Sensitivity Analysis

Self organizing Maps

The exploration of the design space enables to use Self organizing Maps (SOM) to derive correlation between the design variables and the desired performances. A SOM is a type of artificial neural network trained using unsupervised learning to produce a two dimensional representation of the input space of the data [3]. SOM are useful for visualizing low dimensional views of high dimensional data.

Figure 4 illustrates the benefits of the SOM. It is easy to notice that the high value of the fuel capacity (Coef-Fuel) and the high value of the approach speed (Vapp) are in this case correlated.

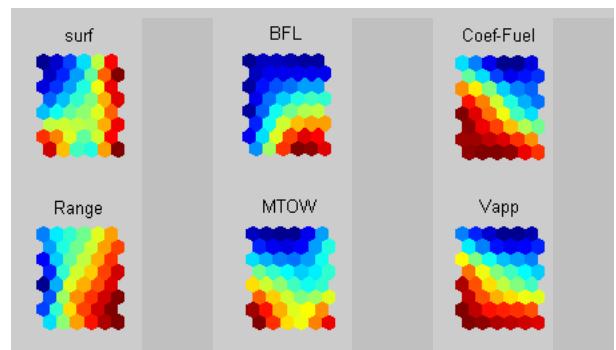


Fig. 4 Example of SOM representation

It is important to stress that the SOM post-processing is more qualitative than quantitative. Its primary aim is to guide the designer into building an intuition regarding the influence of the design variables on the objectives and the possible correlations between objectives. SOM are not intended to compute accurate sensitivities.

Analysis of variance

Variance based methods (or ANOVA) offer a more quantitative evaluations of the sensitivities of the outputs with respect to the design variables. This class of method is based on the estimation of the variance of the conditional expectation of a given output taken all over the possible values of the design parameters [4].

Figure 5 presents a graphical representation of an analysis of variance. On the left hand side of the graph, the green bars represent the total variation of the outputs of interest whilst the yellow bars represent the variation of the outputs actually due a given design variable. The right hand side of the chart represents the impact of the chosen design variables over the desired outputs functions with an estimate of the sign of the influence.

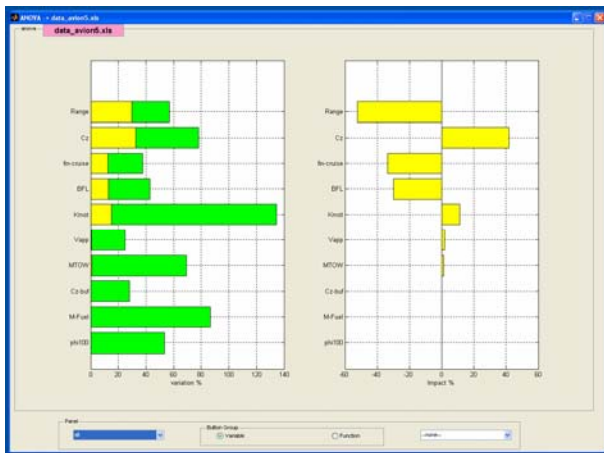


Fig. 5 Variance Analysis plot

7.1 Interactive exploration

Surrogate models [5] are automatically constructed in the visualization tool and are used to interactively explore the design space. For instance, it is possible to visualize the evolution of the feasible domain (see figure 6) when the value of the design parameters or the requirements are changed.

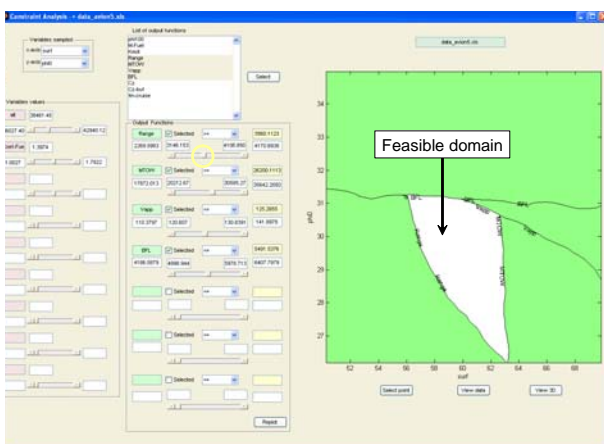


Fig. 6 Visualization of feasible domain

In figure 7 five different parameters are displayed at the same time. Using the idea proposed in [6] in addition to the three axes, the size and the colour of the point are also attached to the value of a variable or an output function. Filters can be applied to interactively visualize the evolution of the design space.

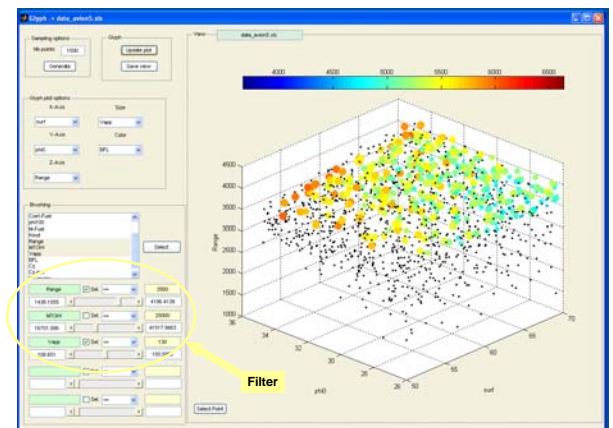


Fig. 7 Glyph representation of 5 different variables

Scatter plots are very useful to visualize the distribution of functions and their correlation. In this type of representation the Pareto frontiers are clearly seen and here again filters can be used to select preferred area of the design space. In figure 8 the red dots are filtered out and the black dots represent the design of interest.

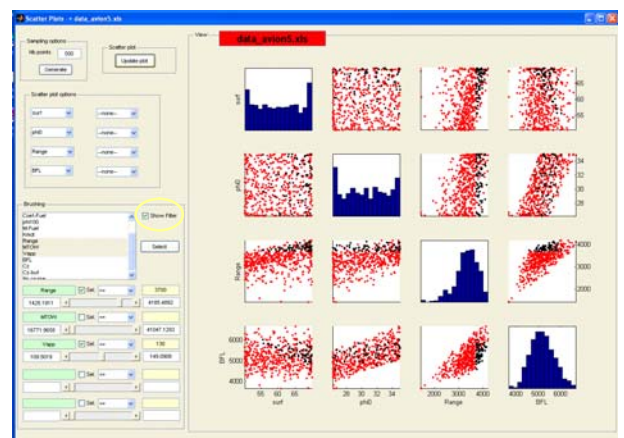


Fig. 8 Interactive filtering on scatter plots

8 Example of a trade off analysis

The use of the methodology is illustrated in the trade off analysis between the size of a

winglet and the aspect ratio of the wing.

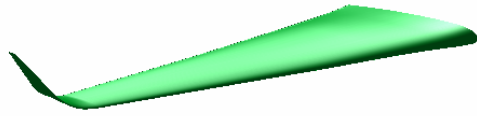


Fig. 9 Geometry of the wing with winglet

8.1 Parametric models

The first step is to construct surrogate models of the relevant phenomena with the required accuracy. In this case, two high fidelity analysis and optimization are used to build the parametric models for the aerodynamic coefficients and the structural mass.

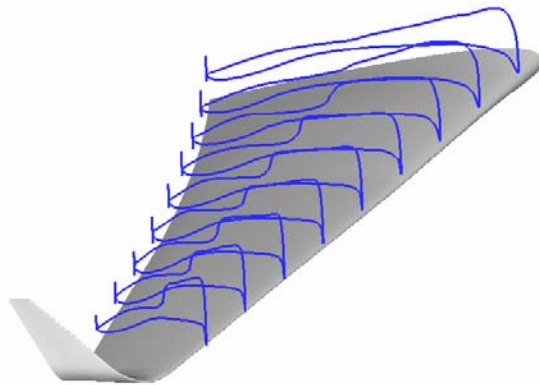


Fig. 10 Pressure coefficient on the wing

Figure 10 presents the pressure coefficient obtained after an optimization of the twist angles along the wing using a Reynolds Average Navier Stokes code.

Similarly, the structural weight is evaluated using a FEM analysis for both the static loads and the flutter cases to take into account the possible weight of the ballast. An example of the stresses in the wing is presented in figure 11.

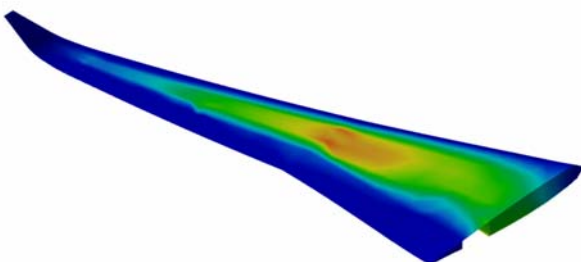


Fig. 11 Structural stresses for a static load case.

A Design of Experiment (DOE) is generated over the domain of variation of the winglet size and the aspect ratio of the wing. A space filling DOE is used to construct the parametric models of the aerodynamic coefficients and the structural weight.

8.2 Design using the surrogate models.

The surrogate models are then used to generate families of aircrafts using our Multi-Level MDO technique. In this case two different families are considered. One is based on minimum fuel consumption at the long range cruise Mach number and the other is based on a minimum structural weight. In both cases the range at the economic cruise regime is the same as well as the constraints for the low speed performances.

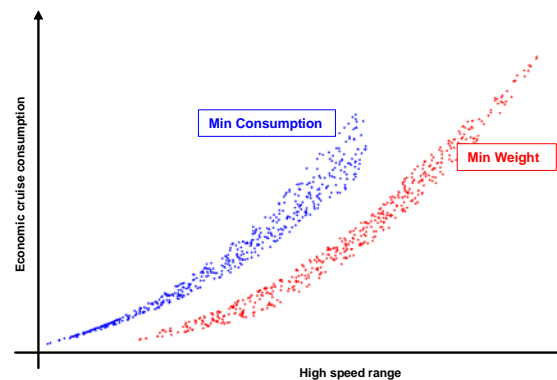


Fig. 12 Trade off long range consumption vs. high speed range

For both cases, several MDO analysis are performed according to a Design of Experiment from which surrogate models are constructed and used to interactively explore the design space. Using these surrogate models hundred of new design can be generated instantaneously. Figure 12 presents the trade off between the fuel consumption at the long range Mach number and the range at high speed for the two design strategies. The Pareto frontiers for the two design strategies are clearly visible.

In the same manner it is also possible to directly compare the two design families. Using the surrogate models the difference of the fuel consumption at the long range Mach number between the designs based on the minimization of the fuel consumption and the design based on

the minimization is computed for hundred of design spanning the intervals of variation of the winglet size and the aspect ratio. Figure 13 shows this difference across the entire design space.

One can see in figure 13 that the design aimed at minimizing the fuel consumption are always more efficient with respect to this criteria whereas the designs based of the minimum structural weight offer a better compromised between the long range cruise and the high speed cruise.

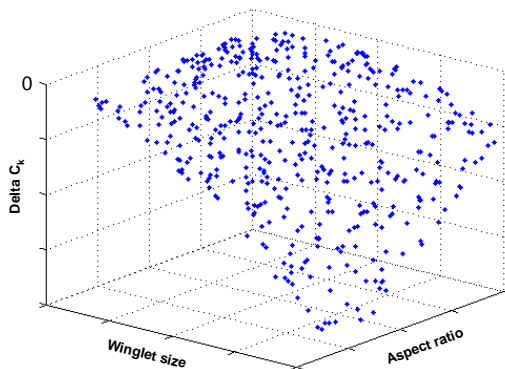


Fig. 13 Difference of fuel consumption between the two families

The "best" solution depends on the weight that the decision makers put on one or the other aspect. These results can be further analyzed using Multi Criteria decision making techniques [7] and a ranking among the solution can be interactively computed based on the preferences of the decision makers.

9 Conclusions

The use of surrogate models at different levels in the design process and its analysis enables a lot of flexibility in terms of scenario of design and easy exploration of the design space. Since the expansive high fidelity analyses are performed once and for all it is possible to formulate many design scenarios with the same raw data. The capability of generating hundreds or even thousands of design at no cost allows the exploration of the different solutions using interactive visualization. The domains that may

generate the highest yield can be identified and then investigated more thoroughly.

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