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Integrate Engine Manufacturer's Knowledge into the Preliminary Aircraft Sizing Process

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Executive summary

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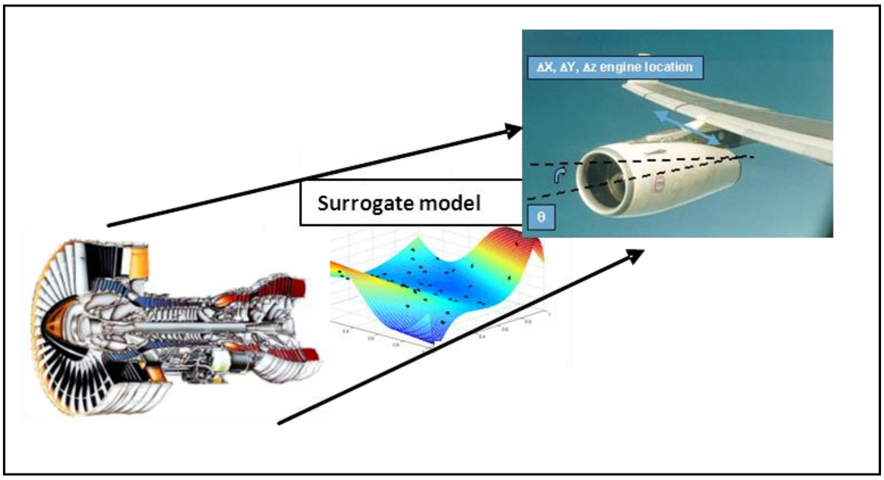

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Knowledge area(s)
Collaborative Engineering and Design

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Surrogate modelling
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Problem area
During the aircraft preliminary design phase, the aircraft manufacturer needs to provide the engine manufacturer with a set of engine requirements for driving the development of consequential engine configurations. At this stage engine performance requirements are not converged and are subject to uncertainty. The preliminary aircraft sizing process is based on coarse-grain/low-fidelity models and empirical and expert knowledge. In the meantime, the engine manufacturer is required to develop future engine design concepts aligned with requests from the aircraft manufacturer. The product design process can be improved if the behaviours of the aircraft and engine designs are analysed simultaneously and in an integrated way.

Description of work
In the context of the EU FP7 project CRESCENDO a collaborative process has been set up and assessed. Within this process detailed information on the behaviour of designed engines has been integrated into an aircraft preliminary sizing tool by means of surrogate modelling. The integration of the engine design information has been performed in three steps. Rolls-Royce Deutschland as engine manufacturer first created a data set of detailed engine simulation results. Next, NLR as a simulation service provider derived a predictive surrogate model from these

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simulation results. Finally, the surrogate model was integrated into the aircraft preliminary sizing tool used by Airbus France, the aircraft manufacturer.

Results and conclusions
A new way of working has been assessed in which the aircraft manufacturer, the engine manufacturer and simulation service providers collaboratively mature the engine requirements during the preliminary design phase.
The engine surrogate model has been invoked as a black-box from within the aircraft preliminary design optimisation loops carried out by the engine manufacturer. The surrogate model reduces the uncertainty of coarse-grain formulas and may result in more competitive aircraft and engine designs.
The surrogate model has been integrated in a collaborative cross-organisational workflow between aircraft manufacturer, engine manufacturer and simulation service providers to prepare for its deployment in industrial preliminary design processes.

Applicability
The new collaborative way of working between aircraft manufacturer, engine manufacturer and simulation service providers could contribute to removing time consuming rework cycles in early and subsequent design stages while delivering the optimal aircraft-engine combination.
The assessed process, applying an innovative collaboration standard, provides the opportunity to introduce useful design iterations with much more enriched information than in the classical design process as performed today.
Specifically the application of an engine surrogate model is advantageous as it allows for extensive trade-off studies on aircraft level because of the low computational effort while the intellectual property of the engine manufacturer is respected and kept in-house.
The described collaborative approach may be extended to create surrogate models of the behaviour of aircraft parts, components or equipment other than engines as well.

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Integrate Engine Manufacturer's Knowledge into the Preliminary Aircraft Sizing Process

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Abstract

Purpose – To set up and assess a new method to collaboratively mature the requirements for engine development in a more efficient way during the preliminary design phase.

Design/methodology/approach – A collaborative process has been set up in which detailed information on the behaviour of designed engines has been integrated into the aircraft preliminary sizing process by means of surrogate modelling.

Findings – The engine surrogate model has been invoked as a black-box from within the aircraft preliminary design optimisation loops. The surrogate model reduces the uncertainty of coarse-grain formulas and may result in more competitive aircraft and engine designs. The surrogate model has been integrated in a collaborative cross-organisational workflow between aircraft manufacturer, engine manufacturer and simulation service providers to prepare for its deployment in industrial preliminary design processes.

Practical implications – The new collaborative way of working between aircraft manufacturer, engine manufacturer and simulation service providers could contribute to remove time consuming rework cycles in early and later design stages within delivering the optimal aircraft-engine combination.

Originality/value – The assessed process, based on an innovative collaboration standard, provides the opportunity to introduce useful design iterations with much more enriched information than in the classical design process as performed today. Specifically the application of an engine surrogate model is advantageous as it allows for extensive trade-off studies on aircraft level because of the low computational effort while the intellectual property of the engine manufacturer (the engine preliminary design process) is respected and kept in-house.

Keywords Surrogate modelling, collaboration, engine design, aircraft sizing, preliminary design, optimisation.

Paper type *Technical paper*.

Introduction

During the aircraft preliminary design phase the aircraft manufacturer needs to provide the engine manufacturer with a set of engine requirements for driving and influencing the development of consequential engine configurations. At this stage engine performance requirements are not converged and are subject to uncertainty. The preliminary aircraft sizing process is based on coarse-grain/ low-fidelity models and empirical and experts' knowledge. Assumptions concerning the engine behaviour are made without having an engine model representing the real physics. In the meantime the engine manufacturer is required to develop future engine design concepts aligned with requests from the aircraft manufacturer. The product design process can be improved if the behaviours of the aircraft and engine designs are analysed simultaneously and in an integrated way: optimising the aircraft design using a 'flexible' engine. In aircraft design literature (Raymer, 2006) the application of a flexible engine model, referred to as a 'rubber engine' is a common step during the preliminary design phase but usually does not involve engine behaviour as predicted by the engine manufacturer.

Aero-engines are complex systems and their behaviour can be predicted sufficiently accurate only after the particular engine design has been reviewed and evaluated by engine experts. Therefore it is cumbersome to integrate this process into the aircraft design process directly. Furthermore, the engine is designed and manufactured by a different company than the aircraft manufacturer. Protection of intellectual property prevents the engine manufacturer from sharing the complete engine design analysis process with the aircraft manufacturer. A solution to this problem is the use of surrogate modelling to support the collaboration. In this context a surrogate model is considered a black-box abstraction of a database of detailed (rubber) engine simulation inputs and results representing the engine design and behaviour, ready to use with very low computation time. With a surrogate model the aircraft manufacturer has the flexibility to evaluate various engine designs, while the intellectual property of the engine manufacturer (the engine preliminary design process) is respected and kept in-house. The engine surrogate model is specifically useful for extensive trade-off studies at aircraft level as it requires low computational effort.

The remainder of this paper is structured as follows. The next section further explains the general principles of surrogate modelling. The section after details the development and application of the engine surrogate model in three steps: creating the database of detailed engine simulations, creating the surrogate model and integrating the surrogate model within the aircraft preliminary sizing process. After that, the next section explains - from a collaboration perspective - how the engine surrogate modelling approach has been integrated in a cross-organisational workflow to prepare for industrial deployment. Finally conclusions are drawn.

Surrogate Modelling

In the context of this paper a surrogate model is defined as an analytical expression of the behaviour of a complex system (e.g. an engine). The behaviour of the system itself can be predicted

- by means of real-world experiments with the system, which are usually too expensive,
- or by means of simulation using detailed system simulation models, which requires expert knowledge of the system and computational effort.

Figure 1 illustrates the various levels of representation of system behaviour with their (dis)advantages, including the surrogate model representation. In the remainder of this paper the case of simulating the system with a detailed simulation model will be assumed as the source of the surrogate model. Here the detailed simulation model is a set of coupled highly non-linear systems of algebraic equations representing engine components performance that is simulated through an innovative automated process at the engine manufacturer. Several system simulations are performed for various input settings resulting in a data set of listed input-output combinations, which are called data points. For example, one data point represents one design configuration with the corresponding system behaviour represented in the output values. The sampling of the data points is based on a so called Design-of-Experiment (DoE). The DoE should provide sufficient variability in the input values to cover the desired input range of the surrogate model. Examples of DoEs are full or fractional factorial designs or Latin hypercube sampling (LHS) methods (Simpson, 2001). Once the data set has been produced, a surrogate model can be derived that matches the input-output combinations using numerical approximation techniques, also called data fitting. The surrogate model predicts the system outputs in the available data points but is also able to predict output values in between these data points, see Figure 2. This is useful to evaluate (theoretical) designs that have not been simulated yet by the detailed system models.

Figure 1. Hierarchic view on different system representations

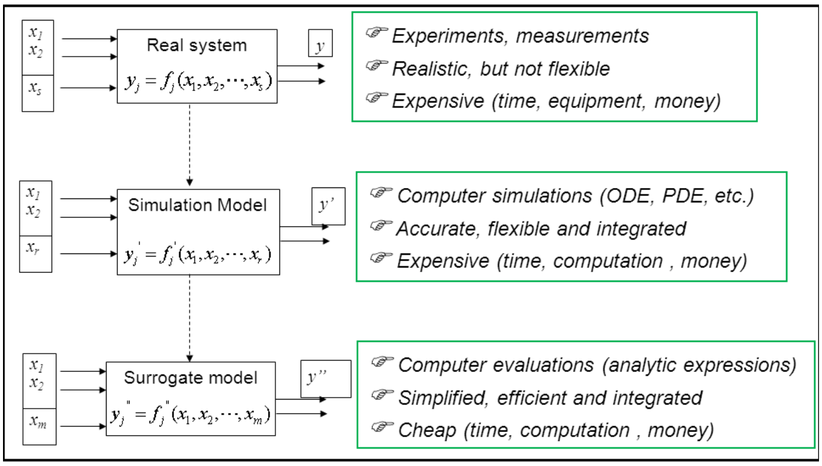
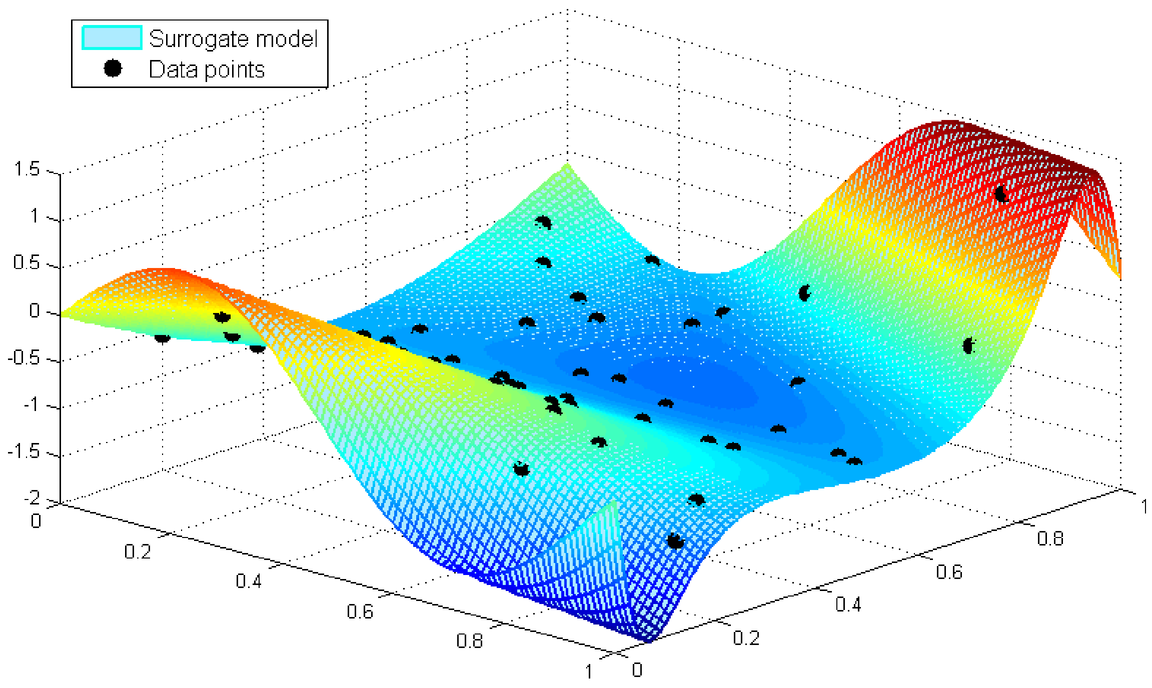


Figure 2. Example plot of a data set (black dots) and a fitted surrogate model (plotted surface)



Several fitting techniques exist. The most common is polynomial regression, also referred to as response surface method (Simpson, 2001). Besides, other methods have been developed with more complicated analytical expressions like artificial neural networks, kriging, radial basis functions, splines, etc. The methods can be divided in interpolation or approximation methods. In case of interpolation the resulting surrogate model exactly matches the data points from which it was created with estimations in between those data points. In case of approximation the surrogate model does not exactly match the data points but approximates them as well as the space in between. The feasibility of a fit method depends on the nature of the data set: if it is high or low dimensional, if it is sampled in a grid or scattered, if it is noisy, if it is sampled in a sparse or dense manner etc. The fitting process is usually supported by dedicated software tools that statistically analyse the data set, provide multiple fit methods and facilitate a fit assessment to select the best method with the appropriate settings. For instance, assessment of a candidate surrogate model is performed by excluding a number of points of the data set from the fit and reserving them for validation afterwards by comparing the surrogate prediction in these points with the true values. This validation data set can be shifted across the complete data set to have a better validation range: cross-validation. In case of approximation methods the comparison between the predictions in the fitted data points and the true values already provides a metric for the validation. Several error metrics are available to represent the validation, e.g. root mean square error (RMSE), mean absolute percentage error (MAPE), R-squared test and quantile tests (Kleijnen, 2000).

Engine surrogate model

This section describes the collaborative work performed and the achieved results on the development of an engine surrogate model. It consists of three parts:

- The process of creating a data set of detailed engine simulations by the engine manufacturer (Rolls-Royce Deutschland)
- The creation of the surrogate model by a simulation service provider (NLR)
- The integration of the surrogate model with the aircraft preliminary sizing tool used by the aircraft manufacturer (Airbus France).

Detailed engine simulations

Typically the engine design process starts with the request formulated by an aircraft manufacturer. In this request, external engine requirements like flight conditions and associated take-off, climb and cruise thrusts as well as power and bleed off-takes are provided. In addition, also information like intended entry into service (EIS) date or constraints like maximum allowed fan diameter are specified. Due to the fact that in the preliminary design phase these quantities are still subject to uncertainty, ranges of variation are provided. In addition to these external requirements, the engine manufacturer's preliminary design performance specialists define internal requirements and constraints: they decide about the engine basic concept and architecture (number of shafts, direct-drive or geared turbofan, engine core concept, materials, etc.). Once the list of requirements is complete, the engine performance specialist is able to start the preliminary design. An innovative automated process has been set up for the preliminary design: Computational Preliminary Power Plant Optimisation (C3PO), see Figure 3. To run this process, the following main steps have to be conducted:

- Definition of design and off-design cases against which the cycle shall be designed
- Setup/ calibration of the C3PO component performance modules
- Specification of the Design-of-Experiment (DoE), to ensure the variation of parameters during the process run as requested
- Specification of process control parameters

The C3PO process as illustrated in Figure 3 basically combines the engine performance predictions tool with so called knowledge based engineering (KBE) tools providing estimations for component performances (e.g. component efficiencies, pressure losses, spool speeds and cooling air consumption). This component performance estimation is then automatically fed back into the engine performance predictions tool. Data between the KBE and the performance tool is exchanged until a converged solution is achieved. More information about the automated KBE process can be found in Kupijai (2012).

For the engine surrogate model 400 engine designs have been simulated based on the automated preliminary design process. The following input parameters have been varied within pre-defined ranges using a LHS DoE method:

- Maximum take-off thrust (MTO)
- Maximum climb thrust (MCL)
- Maximum cruise thrust (MCR)
- Fan diameter
- Stator outlet temperature (SOT) at MTO (used for core size adjustment)
- High pressure compressor (HPC) exit temperature (T3) at MTO (used for adjustment of the overall pressure ratio)

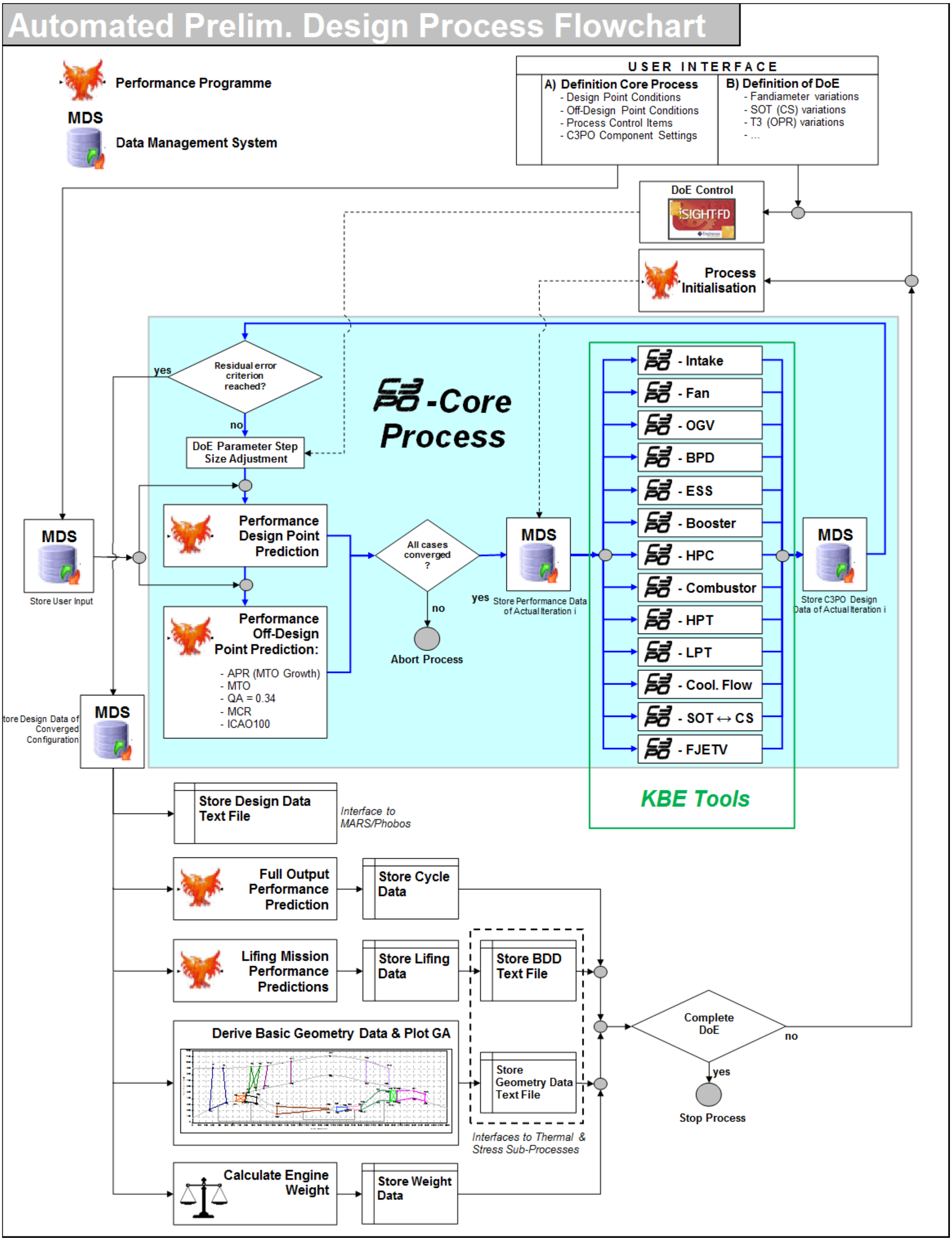
After the automated calculation of the 400 engine configurations, the results were reviewed and filtered by the engine performance specialist and a data set was delivered to NLR for the surrogate model generation containing the following output parameters:

- Fuel flow
- Specific fuel consumption (SFC)
- By-pass ratio (BPR)
- Engine core size
- Overall pressure ratio (OPR)
- Engine inlet flow
- High pressure and Low pressure spool speeds

at MTO, MCL and MCR condition

- Engine weight

Figure 3. Rolls-Royce Deutschland Preliminary Design Process (C3PO) Flowchart

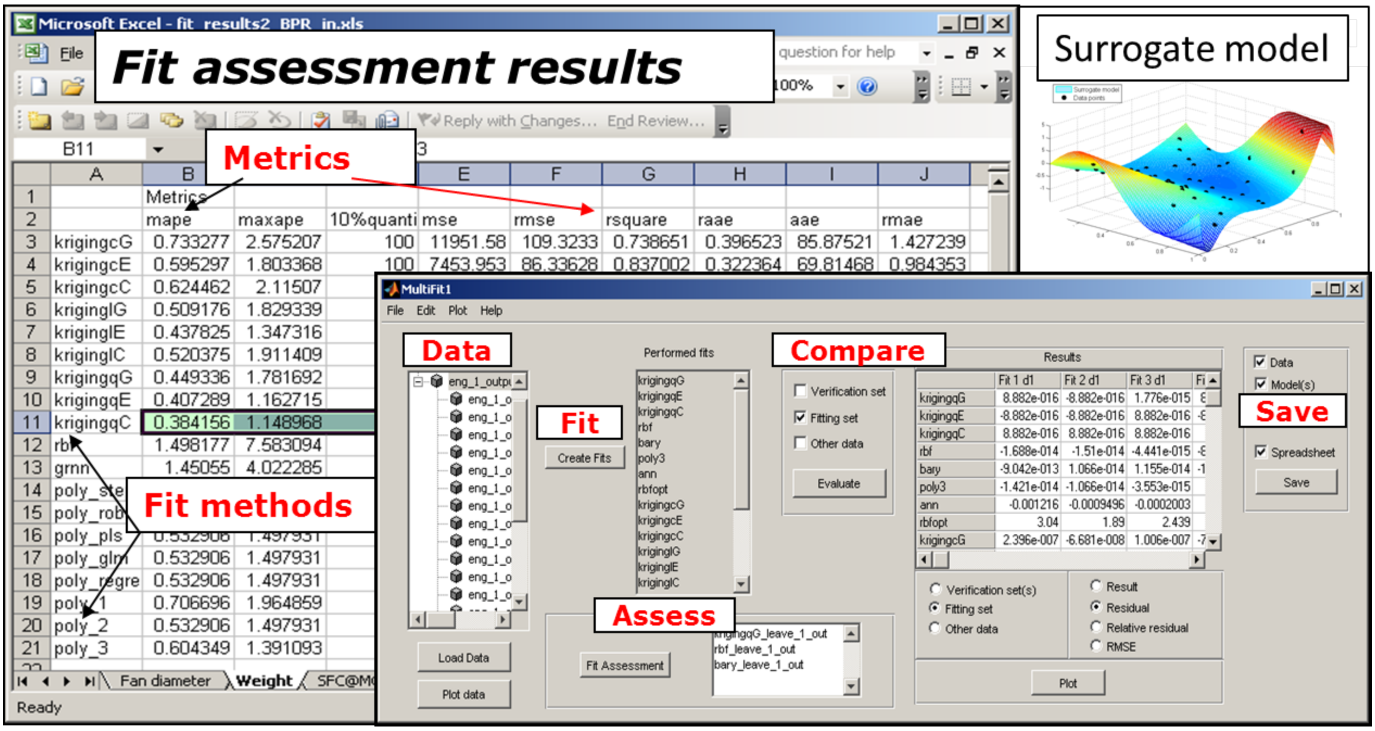


Creation of the surrogate model

Based on the engine data set a 6-dimensional input space (MTO, MCL, MCR, fan diameter, SOT and T3) and a 7-dimensional output space (Engine Weight and SFC & BPR during take-off, climb and cruise) have been identified. Because the aircraft sizing tool expects BPR to be an input and the fan diameter to be an output, the variable BPR (during take-off) has been shifted to the input space and the fan diameter has been shifted to the output space. This does not affect the fitting process because a LHS method was used originally to create the 400 point data set with sufficient variation of the BPR variable, which in fact correlates with the fan diameter.

Various methods and instances of these methods have been used to approximate the data set using NLR's data fitting tool MultiFit (Vankan, 2010). The different fit methods have been assessed using a combination of error metrics on a separated set of validation points, see Figure 4. From this analysis it has been found that the kriging method with quadratic regression and cubic spline correlation produces the best fit. It has a mean relative error of less than 0.5 % in the separated validation points. This method has been used finally to create the engine surrogate model.

Figure 4. Surrogate model creation with MultiFit and fit assessment results

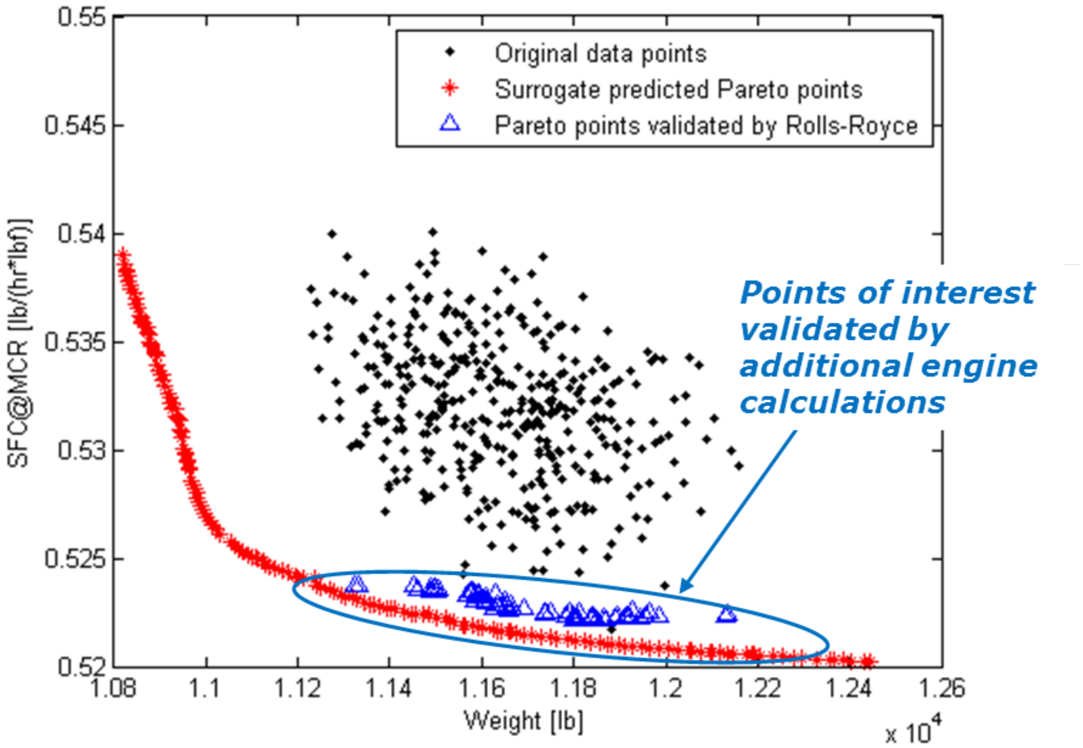


Up until now the performance of the surrogate model has been optimised using the available data set. It may still give extrapolation errors outside this data set. Therefore, the surrogate model has been validated by evaluating additional engine configurations 'outside' the original data set. Typically, optimal configurations with respect to weight and SFC as predicted by the surrogate model are of interest. Therefore a so called Pareto optimal set (Vankan, 2010) of engine configurations is calculated using the surrogate model (see Figure 5). A selection of these Pareto optimal points has been validated by Rolls-Royce Deutschland. A new improved version of the surrogate has then been created, taking into account the additional validated configurations. This approach has two advantages:

- The surrogate model is enriched with additional data.
- New optimal engine configurations are found which were not known yet from the original data set.

This is an iterative process. Additional points can be validated until an acceptable quality has been achieved and the surrogate model is approved by the engine manufacturer.

Figure 5. Comparison (after the first collaborative iteration) of the Engine SFC and Weight values of the original data set (black dots), predictions by the surrogate model in the Pareto optimal range (red * signs) and Pareto optimal points validated by the detailed engine model (blue triangles)

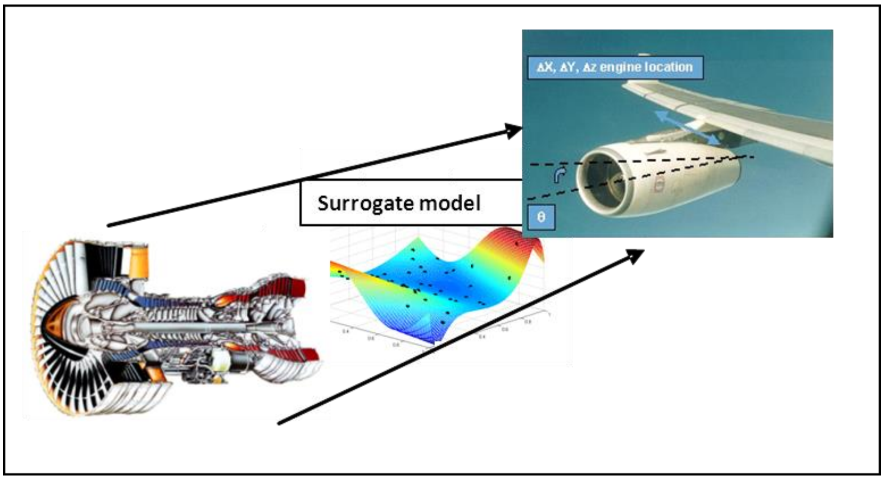


Finally, the engine surrogate model was exported as a black-box executable ready to be invoked from any other tool.

Integration with the aircraft preliminary sizing tool

At Airbus France the aircraft preliminary sizing tool SIMCAD has been used for a preliminary design optimisation of a conceptual aircraft configuration. The SIMCAD tool and the engine surrogate model have been integrated within the AirCADia model-based design and optimisation tool developed by Cranfield University (Guenov, 2010, 2011), to account for robust optimisation and variability of engine performance requirements respectively. Although initial optimal engine configurations were detected already during the creation process of the surrogate model (see previous section) the optimisation is now performed on aircraft level using SIMCAD/AirCADia and following the top-level aircraft requirements. During the optimisation the aircraft sizing model takes advantage of the inclusion of a more detailed engine model, based on information from Rolls-Royce Deutschland: by using the engine surrogate model. This inclusion is illustrated by Figure 6. For the integration into the aircraft sizing process the surrogate model has been adapted to the interfaces of the SIMCAD and AirCADia model. The integrated surrogate model predicts the engine weight, fan diameter and SFC as a function of the Take-off thrust (MTO) and the by-pass ratio (BPR).

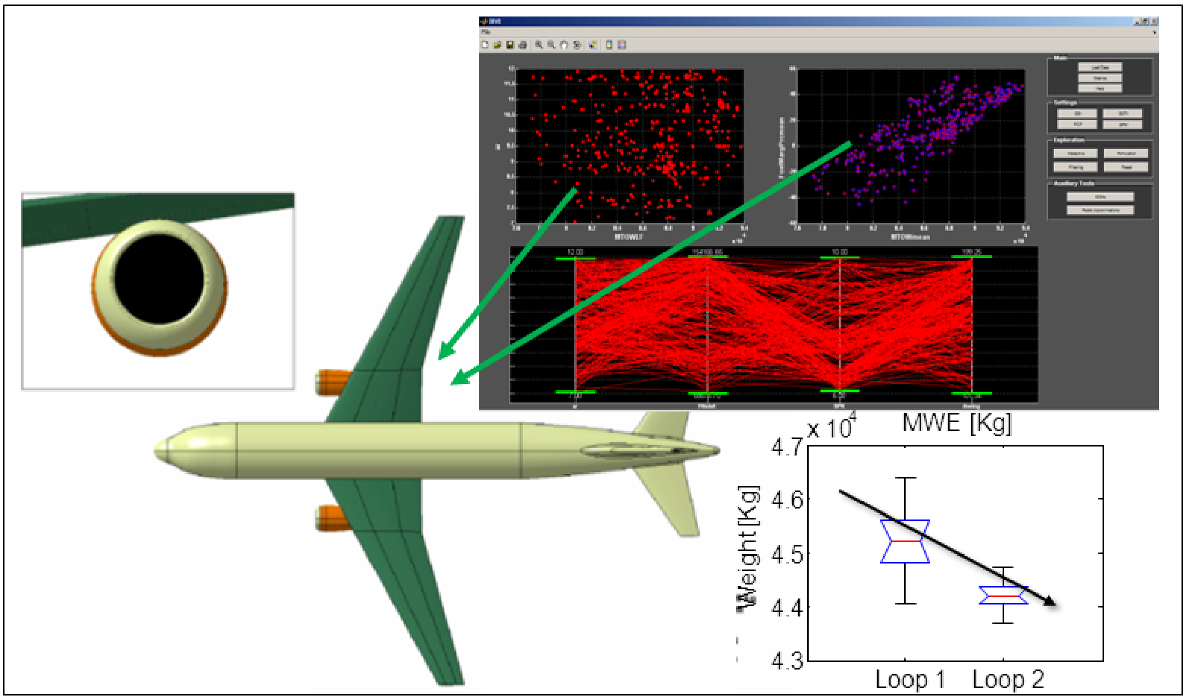
Figure 6. Integration of the engine surrogate model into the aircraft sizing tool



During the aircraft level optimisation the variables sea level static thrust (in the model equal to MTO) and BPR as well as the wing area and wing aspect ratio have been varied as design variables to minimise the maximum take-off weight (MTOW) of the aircraft configuration. An illustration of the results is shown in Figure 7. The upper right part of Figure 7 shows a screenshot of the AirCADia program. In this screenshot the various evaluated aircraft designs are plotted as data points. One data point represents one aircraft configuration. In the two upper sub-graphs the objective variable MTOW is plotted against the wing aspect ratio (left) and against the fuel margin percentage (right). The lower sub-graph of the AirCADia program shows the corresponding values of the four design parameters, interconnected by lines.

In advance to the engine surrogate model integration the same optimisation has been performed with the aircraft model containing simplified engine formulas of SIMCAD. During this optimisation uncertainty margins were added to the engine related variables (as no specific knowledge from the engine manufacturer was involved yet) to find a robust optimal design. Now with the engine surrogate model included the uncertainty margins could be reduced. It should be remarked that the engine surrogate model still has an uncertainty margin (which is inherent to surrogate modelling) but this is considered to be much smaller as now at least specific knowledge from the engine manufacturer is included. While comparing the two optimisation loops the second loop with the engine surrogate model included resulted in a more competitive design and in a smaller uncertainty margin, which allows to significantly reduce the number of iterations between aircraft and engine manufacturer. This is illustrated by the bottom right plot of Figure 7.

Figure 7. Optimisation results with AirCADia [I] and the aircraft sizing tool SIMCAD. One data point represents one aircraft configuration.

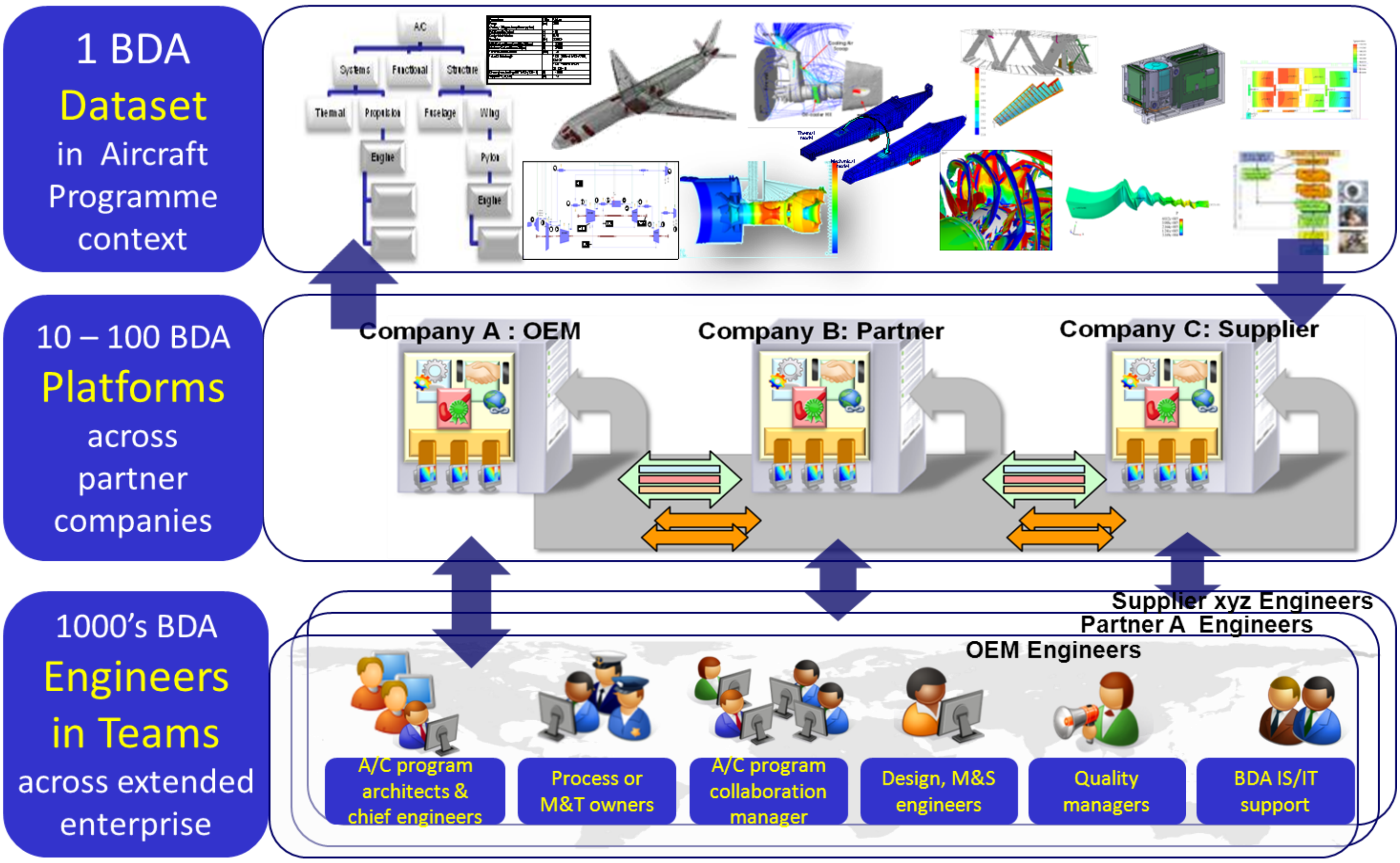


Deployment perspective

To prepare for deployment in industrial preliminary design processes, the method of engine surrogate modelling - as described above – has been integrated in a cross-organisational workflow in which the aircraft manufacturer, engine manufacturer and simulation service providers collaboratively mature the engine requirements. The setup of the cross-organisational workflow has been based on the “Behavioural Digital Aircraft (BDA) developed in the EU 7th Framework project CRESCENDO (www.crescendo-fp7.eu). This project addresses the critical challenge to ensure product maturity (at all levels) at entry into service, by improving the management and evolution of the Aircraft Behavioural Dataset from concept to certification. The ambition of CRESCENDO is to initiate a step change in the way that Modelling and Simulation activities are carried out, by multi-disciplinary teams working as part of a collaborative enterprise, in order to develop new aeronautical products in a more cost and time efficient manner. The major result of the CRESCENDO project is the so called “Behavioural Digital Aircraft” (BDA), which consists of three key concepts: (illustrated in Figure 8).

- The BDA data set is considered as a multi-partner, multi-level, multi-discipline, multi-quality behavioural digital representation of the evolving Aircraft and all its constituent systems and sub-systems. A single, but federated, BDA data set would typically exist for a given major aircraft development program.
- BDA platforms implement collaborative services solutions and behavioural multi-physics simulation capabilities to manage, manipulate, preserve, re-use and enrich all the models & associative data needed to create, evolve & mature the BDA data set. Several instances of BDA platforms would typically exist across the collaborative enterprise. The aim for CRESCENDO is to define a generic BDA architecture specification that any given platform implementation should comply with. However, different aircraft and engine manufacturers, partners and suppliers may need to use only part of the complete functional specification, and may choose different vendor solutions to implement the BDA platform for their organisations.
- Finally, it is envisaged that there could typically be thousands of potential users, collaborating in teams across the extended enterprise, creating and sharing their information more efficiently through the BDA platforms, to create and build the BDA data set. Such users range from aircraft program architects and chief engineers, through to teams of design, modelling and simulation engineers, supported by IS/IT specialists.

Figure 8. Illustration of the Behavioural Digital Aircraft (BDA) concept as developed in CRESCENDO (Coleman, 2012)



The engine surrogate model case as described in this paper has been used as one of many validations and demonstrations of the BDA concept. A new way of working has been demonstrated in which the aircraft manufacturer, the engine manufacturer and simulation service providers collaboratively mature the engine requirements during the preliminary design phase. Throughout the demonstration the focus has been put on the collaborative aspects with many different types of organisations involved. Besides the development of an engine surrogate model, specific requirements on the engine power and bleed off-takes were simulated by another simulation service provider (DLR). Requirements, models and simulation results have been shared in a secured way through the BDA while each partner used its local life-cycle management and simulation tools. Usually, partners in the extended enterprise (e.g. aircraft and engine manufacturer) are operating heterogeneous simulation platforms & tools resulting in a non-integrated and non-traceable simulation design & analysis process. The developers of the applicable life-cycle management and simulation tools have adapted and tailored their software such that a multi-partner collaboration by means of data sharing could be realized, compliant with the innovative BDA standard. To further demonstrate the capabilities in the field of collaborative simulation, the engine surrogate model has been invoked during the aircraft design optimisation loop at Airbus France, while still residing at NLR (where it was created) in a cross-organisational co-simulation. A specific service has been developed to facilitate such cross-organisational co-simulation which is explained in Baalbergen (2012).

Conclusion

This paper has described a method to integrate detailed information on engine design behaviour into the aircraft preliminary sizing process: by means of surrogate modelling. This method was applied in a collaborative design study performed by Airbus France, Rolls-Royce Deutschland, NLR and many more partners, based on an innovative collaboration standard. A new way of working has been assessed in which the aircraft manufacturer, the engine manufacturer and simulation service providers collaboratively mature the engine requirements during the preliminary design phase. It can be concluded that the innovative collaborative approach is feasible and that it provides the opportunity to introduce useful design iterations with much more enriched information than in the classical design process as performed today. It contributes to a more robust aircraft architecture considering the integration of the engine in pre-design and it could contribute to remove time consuming rework cycles in early and later design stages within delivering the optimal aircraft-engine combination. Specifically the application of an engine surrogate model is advantageous as it allows for extensive trade-off studies at aircraft level because of the low computational effort while the intellectual property of the engine manufacturer (the engine preliminary design process) is respected and kept in-house. In the current study the engine surrogate model predicts the engine weight, fan diameter and specific fuel consumption as a function of the take-off thrust and the by-pass ratio. Future versions of the model could also address other important engine requirements like entry into service and emissions. Furthermore, the described collaborative approach may be extended to create surrogate models of the behaviour of aircraft parts, components or equipment other than engines as well.

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[I] http://www.cranfield.ac.uk/soe/departments/aerospaceengineering/engineeringdesign/crescendo.html