# Collaborative Robust Engine Design Optimization

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*Abstract: This paper describes some of the major contents of the set up and technical coupled simulations within an extended enterprise as developed during the European FP7 research project CRESCENDO (2009-2012). Focus is given on the execution of simulation processes (workflows) for collaborative engineering design tasks in the aeronautical industry towards the ability to perform optimization and robust design studies. Different types of simulation workflows will be explained, such as event or process driven under the aspects of low, medium or high frequency access and execution. An industrial example of the implementation of a high frequency process driven workflow in the extended enterprise shall give an impression of the developed workflow execution capabilities in the case of an aero engine design application.*

*Keywords: Aero Engine, Design Optimization, Robust Optimization, Collaborative Engineering, Isight, SEE*

## 1. Introduction

Within the European CRESCENDO (Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimization) research project (Anonymous 2009), Rolls-Royce Deutschland Ltd & CoKG (RR-D) was the focal point for a test case called "robust detailed design" in a collaborative partner environment. As part of this test case, a demonstration of a "Collaborative Robust Engine Design Optimization (CREDO)" was given during the CRESCENDO public forum in Toulouse in 2012 (Anonymous, 2012).

Although an automated process for robust design optimization (simulation workflow) for engine components or modules of an engine can become already a major challenge for a single company, the consideration of a collaborative partner environment, including the definition, exchange and distribution of interface data and results between the partners, increases significantly the level of effort. So one of the major challenges was the set up of the collaborative design workflows enabling coupled simulations with many high frequency executable design iterations under consideration of IT-security constraints. Advanced simulation techniques, appropriate optimization and robust design methods, and visualization of the achieved results were also considered in this test case.

There are two major aspects for the collaborative design tasks:

1. The ability to exchange data via a collaboration hub or data repository
2. The ability to execute simulation commands many times (high frequency execution) between partner companies for coupled simulation studies

The first point is realistic to achieve because there are existing professional data management systems which enable partners to up- and download data. The second point is much harder to achieve because of the access to different partner company simulation environments. Usually such simulation frameworks are internally driven and all IT is principally blocked from the outside world. Security and proprietary aspects do play a major role and the risk of encountering intruders has always to be minimized. One solution for such types of high frequency driven coupled simulations is the SIMULIA Execution Engine (SEE) in addition to the process integration software Isight.

This paper describes the different types of simulation workflows, such as event or process driven under the aspects of low, medium or high frequency access and execution. An industrial example of the implementation of a high frequency process driven workflow in the extended enterprise - CREDO - shall give an impression of the developed workflow execution capabilities.

Previous research work on this subject was done in the VIVACE project and some collaborative design studies are documented in (Parchem et al., 2010) and (Wenzel et al., 2010).

## 2. Executing Simulation Workflows in the Extended Enterprise

During the CRESCENDO project, two different characterizations of simulation workflows emerged:

1. event driven vs. process driven workflows
2. low-, medium- and high frequency workflows

For the first characterization, a process driven workflow is defined by the availability of a very detailed template, where all parameters, data and information necessary for executing the workflow are given a priori, before the workflow is started.

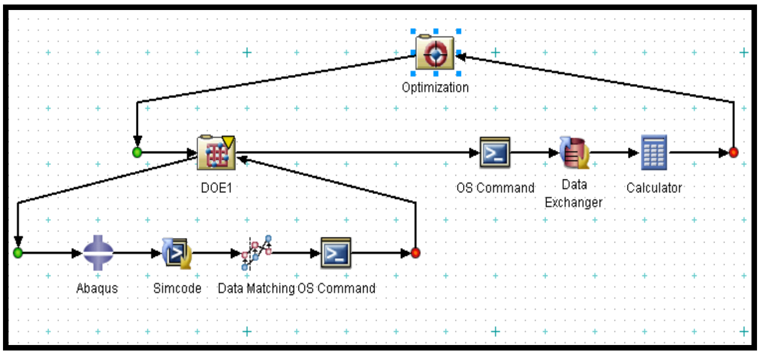


**Figure 1. Isight model as an example of a process driven workflow**

One example of such a process driven workflow template is an Isight model as shown in Figure 1. The execution sequence is the most important feature and consequently shown in the main view. The data flow is de-coupled from that and presented in another view of the process. It follows mainly the process steps, where the data is created or consumed.

In contrast to this, in an event driven workflow, the exact information necessary for or produced of any simulation process step does not have to be known before it is initiated. Parameters and data can be added to the workflow as it executes. Often even the exact next step in the sequence can only be determined when the results of the previous step are available and analyzed.

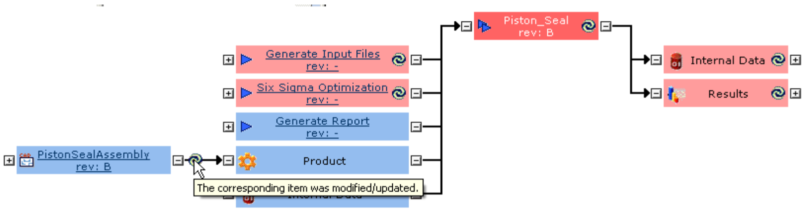


**Figure 2. Impact graph as visualization of an event driven workflow**

A typical visualization of an event driven workflow is the impact graph of the simulation lifecycle management (SLM), shown in Figure 2. The processes are only the links between the different data items. This impact graph is generated a posteriori, when the workflow has been executed.

By its nature an event driven workflow is manual, whereas process driven workflows can be automated. In the CRESCENDO project, both types were implemented, where sometimes an automated process driven workflow was one execution step in an event driven workflow (Coleman 2012).

The other type of workflow characterization used within the CRESCENDO project is based on the number of times a workflow instance is iterated.

If it is iterated only once or a few times, it is called a low frequency workflow. Manual execution is then possible and in fact the norm. All event driven workflows are of that type.

Also, the overhead of manual communication with the central data management system developed in the CRESCENDO project, the BDA hub (Murton; Shaw. 2012), is of little concern here and can be done via a lightweight web interface running in a browser session.

If a workflow instance is iterated about ten to a few hundreds of times, it is called a mid frequency workflow. It no longer can be executed manually, but needs to be automated. In the extended enterprise context that the CRESCENDO project explored, this implies that simulation executions at remote partner sites need to be triggered and input and output data needs to be communicated between the partners programmatically.

The typical solution in the CRESCENDO project to this challenge was a polling mechanism already proposed within the VIVACE project (Wenzel et al., 2010). Here the BDA hub served as the common ground, where the simulation data and trigger signals were shared, which in turn initiated local workflow execution based on remote events (Baalbergen et al., 2012).

This polling mechanism is very light on IT requirements, but implies a considerable overhead in the execution time of remote simulations. This renders it unsuited for executing high frequency workflows, where the number of iterations is a few hundred at least.

Here a direct partner to partner execution must be used that eliminates any unnecessary communication overhead. This requirement also dictates that the local network of a company must be opened to the partners in such a way that they can request simulation executions and communicate input and output data.

In the CRESCENDO project one partner company developed their own solution, where all others that executed high frequency workflows in the extended enterprise used the business to business (B2B) functionality of the SIMULIA Execution Engine (SEE). This feature is based on the JEE certified middleware the SEE is implemented on and guarantees a secured, encrypted data exchange together with unique authentication of the incoming request through pre shared X.509 certificates and the protection of the IP contained in the local workflows.

## 3. High Frequency Process Driven Simulation Workflow – Example Collaborative Robust Engine Design Optimization


**Figure 3. Collaborative design development of a core engine**

Figure 3 shows a scenario for the development of the core of an aero engine in an extended enterprise with three industrial partners: RR-D in Germany, MTU in Germany and AVIO in Italy. Each of the partners contributes with their specific engine module designs for the high pressure compressor, combustor, and high and low pressure turbines to the overall design of the engine. The main intention is to achieve an engine with the best efficiency and the lowest weight, but also to guarantee the robustness of the engine. Since all of these modules are connected in some way (geometry, pressure, velocity, etc.), the challenge is the consideration of the degree of coupling between these modules for the simulation and therefore for the robust design optimization. This leads to the definition of the overall optimization problem structured into the system and subsystem level investigation. In the past, the development of such engine modules was done mainly locally at each partner company under the constraint of agreed and often rigid interfaces between the modules. This reduces the potential for the optimization of the overall engine. This test case was focused on achieving a high degree of simulation coupling, which requires a high number of coupled design iterations.

Figure 4 explains the goal of the collaborative robust design optimization in a simplified way. Two objectives, the efficiency and weight of the engine, will be optimised. This leads to a Pareto Front as shown in the graph on the left side of Figure 4. Taking then into account uncertainties and variability – for example of the design parameters – could identify the design as not being sufficient robust with regard to the design objectives (probability of failure PoF). Therefore, other points in the design space have to be investigated until a stable region can be found ensuring the robustness. This is shown in the small graph with a steep peak in the curve, which indicates that any variation of the design parameters will cause the objective value (efficiency, weight) to drop down. The history graph downstream of the engine represents the probability of failure for the major objectives of efficiency and weight for a given uncertainty and variability of the design parameters as illustrated in the history graph upstream of the engine. The effort for such a robust design optimization can become high because a very high number of design iterations (samples, runs) have to be performed in order to assess the robustness of a system which can be measured as the probability of failure which should be low. This is the difference from the deterministic optimization, which is not to give specific values, but to give probabilistic values as, for example, the mean value and the standard deviation for the objectives.

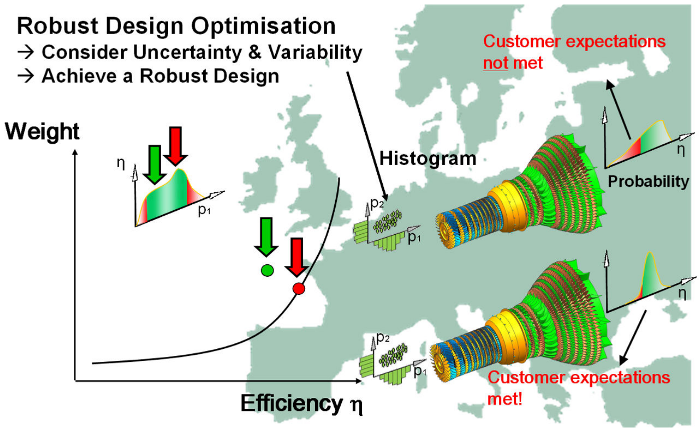


**Figure 4. Robust design optimization target for core engine**

The major requirement to enable collaborative simulations, optimization and robust design studies is the ability to achieve high frequency process driven workflows. This will enable coupled simulation workflows between partners executing a high number of design iterations. The consideration of security aspects and proprietary rights, as required by each partner company, is also a strong challenge. During the CRESCENDO project it did require enormous effort to achieve a secure IT infrastructure with the ability to connect partner's simulation environments. It did become clear that this requirement was quite challenging to be provided in a wide range useable for every partner company, and did remain as a partner issue to be solved. The intention was to provide the capability to deal with different partner-specific IT solutions towards a high frequency execution collaborative simulation process.

Figure 5 shows the IT connection for the coupled simulations between the partners MTU, UBRAND (University of Brandenburg), IRIAS (International Research Institute for Advanced Systems) and the partner AVIO in Italy, together with AVIO's University partners UTORINO (University of Torino) and USALENTO (University of Salento). Some of the test case partners used Isight/SEE from Dassault Systèmes which provides a common solution for tight coupled simulations, since the collaborative workflows can directly be linked via an internet connection. This happened between RR-D in Germany and AVIO (including their partners UTORINO and USALENTO) in Italy for the coupled compressor-combustor optimization. The partner MTU provided a secure web service access to RR-D for their low pressure turbine LPT simulation environment. This enabled a coupled HPT-LPT simulation connection between RR-D and MTU to be achieved. Therefore a specific Isight component was developed by RR-D to provide an automated connection to the MTU web services.

With regard to the SEE connections between the test case partners, a further requirement regarding security aspects was to provide a virtual private network server (VPN). A VPN server installed at the company 24/7 in Potsdam Germany was rented and user accounts were provided to the partners. Although the SEE connection fulfilled the major security aspects, VPN access was installed additionally in order to “channel” the IT connections between the partners protecting it from further intrusion by hackers in the Internet world.

Several test runs were made with the test case partners using the SEE connections, or in case of MTU, the provided web services. With regard to the academic partners, some Design of Experiments studies were tested with the Isight/SEE connection using the optimization algorithms of the academic partners at their local environment and running the simulations at RR-D. It was possible to run a coupled compressor-combustor optimization process between RR-D and the partners from Italy (AVIO, UTORINO, USALENTO) that was stable over more than 24 hours and several thousands of design iterations could been performed.

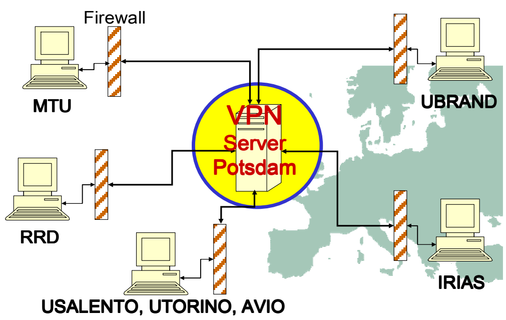


**Figure 5. Simulation connections between the CRESCENDO test case partners**

Two major coupled simulations were performed between

1. the Italy partner group of AVIO, UTORINO, USALENTO and RR-D for the compressor-combustor optimization, and
2. RR-D and MTU for a coupled HPT-LPT simulation,

using the developed IT infrastructure. The coupled simulation between the Italy group is shown in Figure 6. The Isight component “Reference to CC_Model” is the link to the workflow in Italy for the combustor simulation. The overall optimization process is – in this case – controlled by RR-D in Germany.

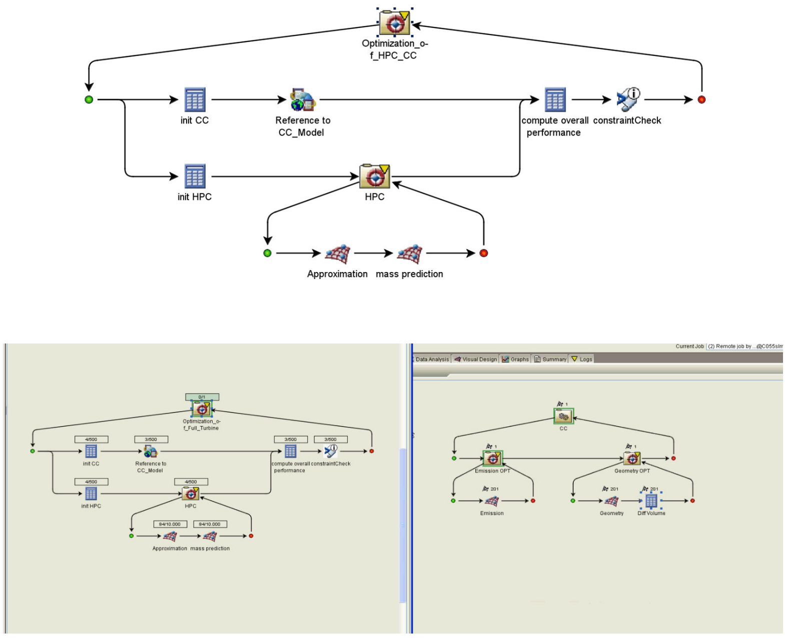


**Figure 6. Coupled compressor-combustor optimization workflow using the SEE**

The whole simulation workflow for the core engine is shown in Figure7. This workflow enables a fully coupled robust design optimization on the system level including the four modules for the compressor, combustor, and high and low pressure turbines on subsystem level, as shown in Figure 7. The modules are coupled over their interfaces (pressure, velocity, radial position of the compressor, etc.). Because of the very high number of design iteration samples required for the robust design optimization (up to $10^7$ runs), surrogate models were used in this workflow in addition to advanced probabilistic methods. Because of simulation time issues, the whole workflow for the engine was run locally on one PC which took about 3 days to produce the probabilistic results for the “probability of failure” - which was minimized by the optimization - against the objectives of weight and efficiency of the engine. Based on the technical set ups for collaborative coupled simulations as described before, it would be possible to replace the local simulation models in Figure 7 by a link/reference to the partners’ simulation environment using the SEE or the Isight web service components in the case of access to the partner MTU. The main goal of this whole workflow for the engine was to demonstrate a fully coupled robust design optimization (with probability of failure prediction) in order to assess the engine design objectives against the customer expectations.

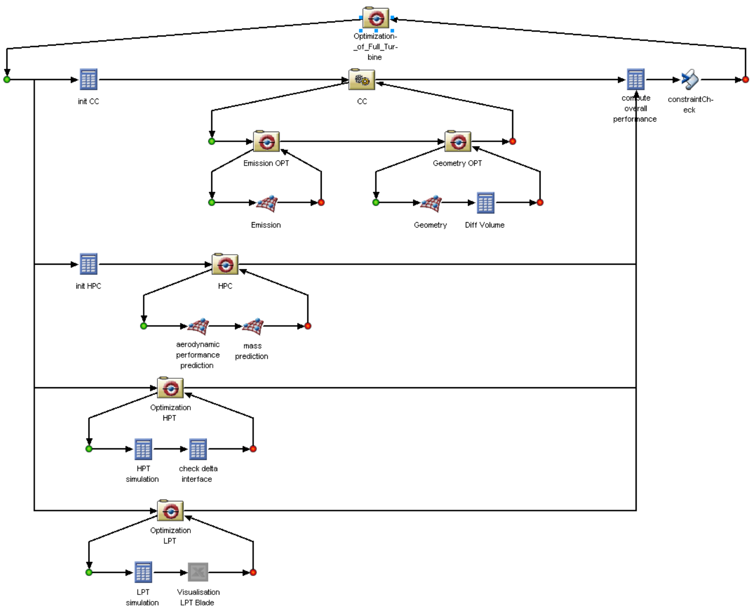


**Figure 7. Process driven robust design optimization workflow for the core engine**

## 4. Conclusions

An industrial example for a process driven high frequency collaborative workflow was demonstrated considering all principal aspects of coupled simulations and robust design optimization techniques. The workflows allow executing a very high number of design iterations as required for optimization and robust design studies. A professional collaborative IT environment was set up with secure and tight connections between the partner companies enabling these coupled simulations. The ability to enable simulation studies on a system level, such as an aero engine design investigation, based on coupled subsystem level simulations - with thousands of design iterations - provides the potential for improved and better aligned product components and modules leading to a robust design solution.

## 5. Acknowledgement

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## 6. References

Anonymous. (2009). *Crescendo Project Homepage.* Available: http://www.crescendo-fp7.eu/. Last accessed 25th Jan 2013.

Anonymous. (2012). *Innovations in Collaborative Modelling and Simulation to Deliver the Behavioural Digital Aircraft.* Available: http://www.crescendo-fp7.eu/pages/crescendo-forum.php. Last accessed 25th Jan 2013.

Baalbergen, E; Lammen, W; Kos, J. (2012). *Mastering Restricted Network Access in Aeronautic Collaborative Engineering across Organizational Boundaries.* Available: http://www.pdteurope.com/media/4838/conference_program_september_sept_20.pdf. Last accessed 25th Jan 2013.

Coleman, P. (2012). *The CRESCENDO Project – Summary of a Key European R&T Initiative and Key Results.* Available: http://www.pdteurope.com/media/4838/conference_program_september_sept_20.pdf. Last accessed 25th Jan 2013.

Murton, A; Shaw, N. (2012). *Developing an Architecture and Standard to Support Innovations in Collaborative Modelling and Simulation.* Available: http://www.pdteurope.com/media/4838/conference_program_september_sept_20.pdf. Last accessed 25th Jan 2013.

Parchem, R; Meissner, B; Nagel, M; Kesseler, E. (2010). *Engine MDO Deployed on a Two-Stage Turbine*. In: Guenov, M. and Kesseler, E. *Advances and Collaborative Civil Aeronautical Multidisciplinary Design Optimization*. Reston: American Institute of Aeronautics and Astronautics. p289-329.

Wenzel, H; Almyren, F; Barner, J; Baalbergen, E; Meissner, B; Lindeblad, M. (2010). *Using the Virtual-Enterprise-Collaboration Hub for Distributed Engine Optimization*. In: Guenov, M. and Kesseler, E. *Advances and Collaborative Civil Aeronautical Multidisciplinary Design Optimization*. Reston: American Institute of Aeronautics and Astronautics. p331-365.