THEME 7 Transport
(including Aeronautics)

Large-scale integrating
project

SEVENTH FRAMEWORK
PROGRAMME

Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation

D0.1.7

CRESCENDO Project
Final Publishable Summary

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PROJECT FINAL REPORT

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NOTE: The CRESCENDO Project Final Report, as submitted electronically via the EC Participant Portal SESAM, consists of 3 distinct parts.

1. This document provides the final publishable summary, including an executive summary and reporting the project context & objectives, main results and potential impact, with relevant contact details and appendices; considered suitable for direct publication by the Commission and written for a wide audience including the general public.
2. The plan for use and dissemination of foreground, submitted separately via SESAM.
3. Report on societal implications, submitted separately via SESAM.

Contents

List of Figures

List of Tables

1 Executive summary of the CRESCENDO project

The "**Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation**" (CRESCENDO) project started in May 2009 and ended in October 2012. This EU FP7 co-funded project was coordinated by Airbus with a consortium of 59 partners from 13 countries, including aircraft and aero-engine manufacturers & suppliers, PLM and simulation software solution providers, research centres and academic institutions.

The following **High-level Objectives** were used to guide and assess the achievable contribution of the results when deployed within the application areas covered during CRESCENDO.

High Level Objectives	Target reduction for CRESCENDO contribution	Assessment of achievable contribution
Development Life Cycle Cost	10%	5.5% - 9.5%
Development Life Cycle Time	10%	4.4%- 9.2%
Rework	50%	30% – 47%
Physical Testing Costs	20%	16% – 21%

The major result has been to develop foundations for the "**Behavioural Digital Aircraft**" (**BDA**), initiating a step change in the use of advanced Simulation Processes & Data Management (SPDM) for collaborative product development. Two categories of enabling technologies were delivered:

- **BDA collaboration capabilities** for managing distributed data, processes and infrastructure. CRESCENDO delivered a generic Business Object Model, web services and Data Exchange (DEX) specifications built on ISO standards; interoperable SPDM platform implementations enabled secure collaborative workflows, with dashboards to monitor progress and assess quality of simulation results; and decision environments were created for aircraft behaviour architects to orchestrate trade studies, and to record key product development decisions.
- **BDA engineering methods** enabling more effective behavioural modelling and simulation processes. CRESCENDO delivered new methods for model preparation using automated meshing and geometric reasoning techniques; surrogate and reduced order modelling; multidisciplinary optimisation strategies; advances in multi-physics coupling with some focus on thermal fluid-structure interactions, aero-thermal and aero-acoustic-vibration modelling.

The applicability of the results was demonstrated in engineering scenarios representative of the **preliminary design** and **detailed definition** phases of the product development lifecycle where the process flow is "design driven by simulation"; and also the **test and certification** phases where the process flow is "design validated by simulation". Four major application areas were considered: **Value Generation, Thermal Aircraft, Power Plant Integration**, and **Virtual Testing,** further decomposed into **17 "Test Cases"**. These provided realistic demonstrations of simulation-based collaborative product development across all phases, and showed the maturity level and value of the enabling BDA collaboration capabilities and BDA engineering methods.

The CRESCENDO project has made its results available to the aeronautics supply chain and related scientific community through: dissemination including the main **CRESCENDO Forum** (and **handbook**) in June 2012, four other industry supply chain events, and more than **90 conference** or **journal publications**; the creation of a **catalogue outlining more than 80 exploitable results** and the **BDA e-Learning portal** for the consortium; and **100 final deliverable documents**. Further information will be found on the CRESCENDO **public website**: www.crescendo-fp7.eu.

Progress in the months following CRESCENDO indicates that the BDA vision is becoming reality in the industrial context, supported by software vendors' solution roadmaps. An industry driven standardisation project[1] is proposed to secure the BDA collaboration standard, and at least two collaborative research projects[2] plan to exploit and further develop results from CRESCENDO.

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[1] Proposal being monitored via ASD-SSG: AeroSpace & Defence Industries Association of Europe Strategic Standardization Group.

[2] EU FP7 co-funded TOICA "Thermal Overall Integrated Conception of Aircraft" project due to start later in 2013; and UK TSB co-funded CONGA "Configuration Optimisation of Next Generation Aircraft" project starting February 2013.

2 Summary of CRESCENDO project context and objectives

2.1 Context and Challenges

The **“Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation” (CRESCENDO)** project started in May 2009 and ended in October 2012. Co-funded under the European Union 7th framework programme, the project was coordinated by Airbus and brought together 59 organisations from 13 different countries. Figure 1 shows the major aircraft and aero-engine manufacturers & suppliers, PLM and simulation software solution providers, research centres and academic institutions, that formed the overall consortium.

Figure 1: The CRESCENDO consortium

In today’s context of global competition, European aircraft, aero-engine and equipment manufacturers, together with their supply chains, face significant challenges impacting new or derivative product development programs.

- The global market, aircraft customers’ expectations and regulatory requirements in the overall air transport system, all demand more efficient and environmentally friendly aircraft to be developed in **shorter timescales** with **greater cost efficiency**;
- Industry globalisation also means manufacturers & suppliers need better **collaboration solutions** to work more effectively as multi-disciplinary teams **across the extended enterprise**;
- Informed **trade studies** are needed to evaluate impacts of **customer expectations** and new technologies on aircraft operational and functional behaviour;
- Effective management of the evolving **aircraft behavioural design data** is needed throughout the development lifecycle to **avoid rework**; better optimisation strategies and multi-physics analysis are needed **to eliminate risks** early in the preliminary design phase and to **accurately predict** functional behaviour in the detail definition phase;
- **Virtual testing methods** are needed to better anticipate and reduce quantity of the real (physical) test activities, supporting the certification phase.

The European aeronautical industry formally recognised these as **Quality** and **Affordability** challenges in the initial Vision 2020[3] and subsequent Strategic Research Agenda[4], particularly in terms of "Creating a competitive supply chain able to halve time-to-market". Systems Engineering was identified as "the holistic approach to creating competitive products", with research areas for "developing new architectures, extending the application of modelling and simulation, through-life product definition, more cost effective verification, validation and certification methods, development of interoperability principles ... and new management systems that will allow these advanced processes to be controlled throughout the extended supply chain".

Figure 2 illustrates the complexity of the changing market, product and enterprise context. Airbus (and the extended enterprise) recognises that there is an increasing need for Systems Engineering as a structured methodological approach to master this complex changing environment.

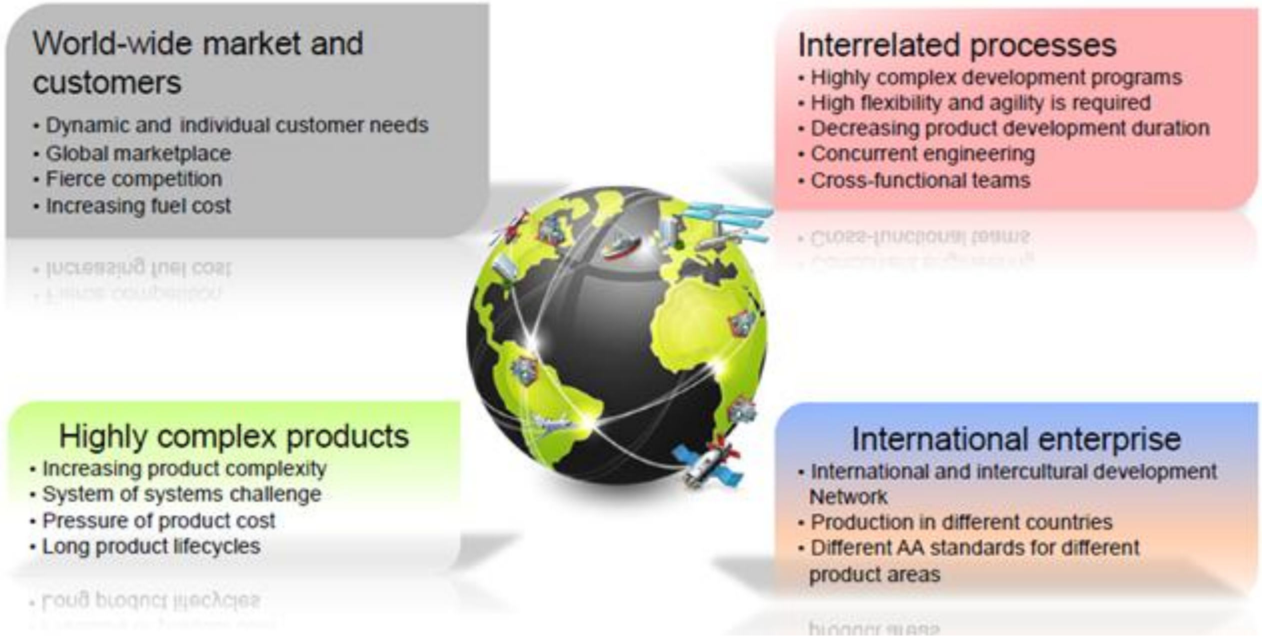

Figure 2: Airbus Context[5]

The specific challenges addressed by the CRESCENDO project are derived from this global context, and can be summarised with three key words[6].

- **Virtualisation:** Conventional methods of design, build and test are no longer efficient. In the future, we must rely on virtual means to identify the most promising concepts and optimised solutions to deliver customer value; to simulate and predict design behaviour; and to test and validate the design in simulated environments.
- **Collaboration:** Today, more than 70% of aircraft systems and components are provided by risk sharing partners and suppliers. In the future, we must find better solutions for collaboration, and establish a common language that will enable us to build the virtual product together.
- **Interoperability:** The optimal product relies on organisations across the extended enterprise using the best design and simulation solutions to suit their competences and activities. In the future, we need interoperability of processes, data and tools to be effective in this heterogeneous environment.

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[3] "European Aeronautics: A Vision for 2020", January 2001

[4] ACARE "Strategic Research Agenda" edition 1, October 2002, and edition 2, October 2004

[5] "Systems Engineering at Airbus", by J. Javelle, at EADS Systems Engineering Forum, Toulouse, October 2012

[6] "CRESCENDO Forum Key Notes", by J. Javelle, at CRESCENDO Forum, Toulouse, June 2012

2.2 Objectives

From the start, the ambition of the CRESCENDO consortium has been 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**.

This ambition can be realised with the objective to develop the foundations for the "**<u>Behavioural Digital Aircraft</u>**" (**BDA**), as the overall means to manage and mature the evolution of the aircraft behavioural characteristics throughout the product development lifecycle, and hence address the critical challenge to ensure maturity at entry into service.

The BDA vision evolved during CRESCENDO (Figure 3) and was used at various dissemination events to illustrate three key concepts associated with the BDA in the extended enterprise.

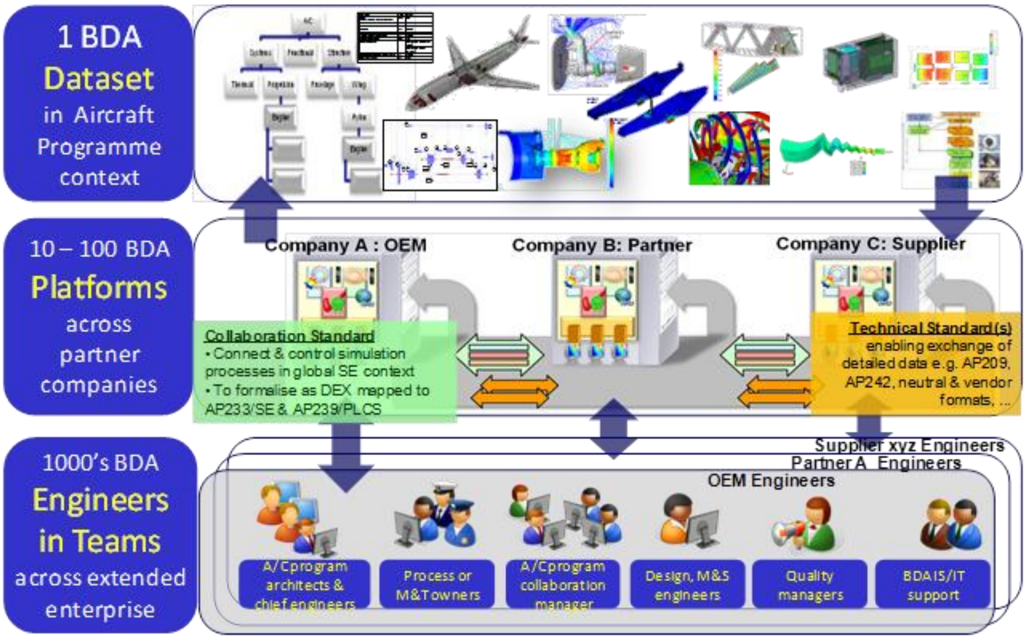


Figure 3: Behavioural Digital Aircraft – Dataset, Platforms and Teams

1. A single, but distributed **<u>BDA dataset</u>** will evolve for a typical major aircraft development program. The objective is a holistic approach to manage all the behavioural models & associative data needed to create an increasingly comprehensive & mature representation of the overall aircraft definition and its constituent systems and sub-systems.
2. Multiple instances of interoperable **<u>BDA platforms</u>** will typically exist across the extended enterprise. The aim for CRESCENDO is that each should use the same generic standards-based information model and web-based collaboration services. However, different aircraft and aero-engine manufacturers, their partners and suppliers may <u>need</u> to use only part of the complete functional specification for their specialist contribution to the BDA dataset; and may <u>choose</u> different vendor solutions and behavioural multi-physics simulation capabilities to implement the BDA platform for their organisations.
3. Finally, the aircraft behaviour architects and multi-disciplinary modelling & simulation teams of the **<u>BDA enterprise</u>** will use their respective BDA platforms, collaborating more effectively as they create & share information to evolve the BDA dataset from concept to certification.

In terms of measuring the potential impact of the results, when deployed and exploited, the following **<u>High-level Objectives</u>** were used to guide and assess the contribution that could be achieved within the scope of the application areas covered during the CRESCENDO project:

- **Contribution towards 10% reduction of development lifecycle duration and cost;**
- **Contribution towards 50% reduction in rework, and finally;**
- **Contribution towards 20% reduction in the cost of physical tests.**

To achieve these ambitious objectives, the CRESCENDO project work plan[7] was carried out through six “sub-projects” (further divided into 27 work packages) using an iterative approach based on Systems Engineering principles. The main technical objectives were to develop an overall **BDA architecture** to realise the vision, and to demonstrate and validate the impact across **17 test cases** that together represent four challenging use cases: **Value Generation, Thermal Aircraft, Power Plant Integration**, and **Virtual Testing**. The process to develop the BDA architecture is shown schematically in Figure 4.

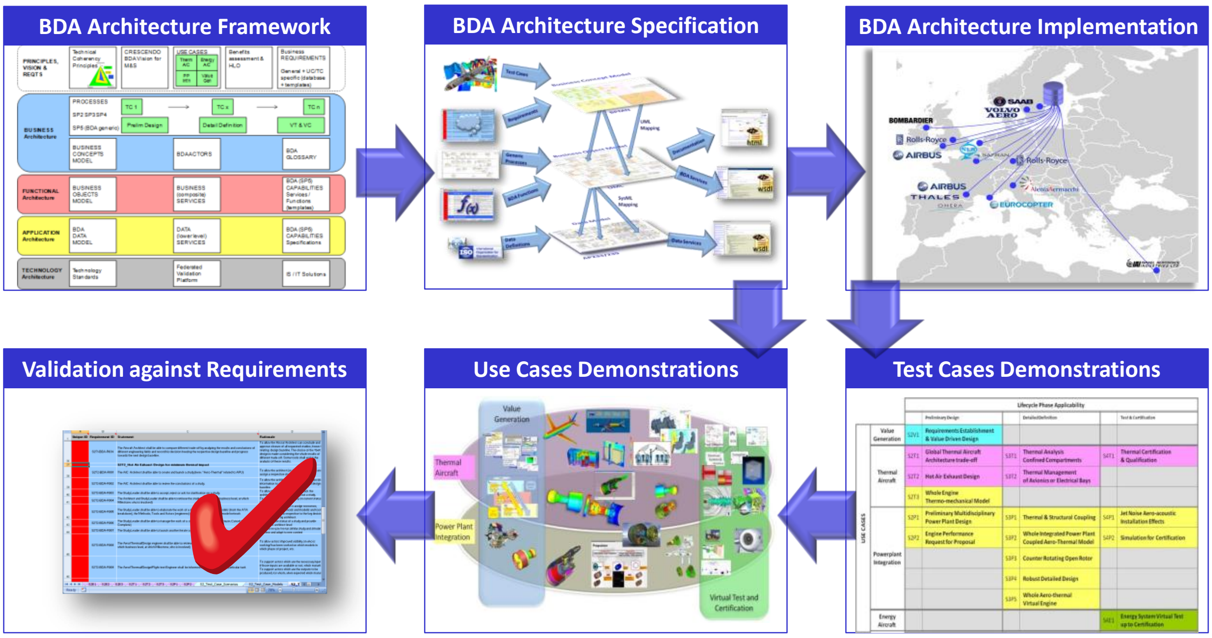
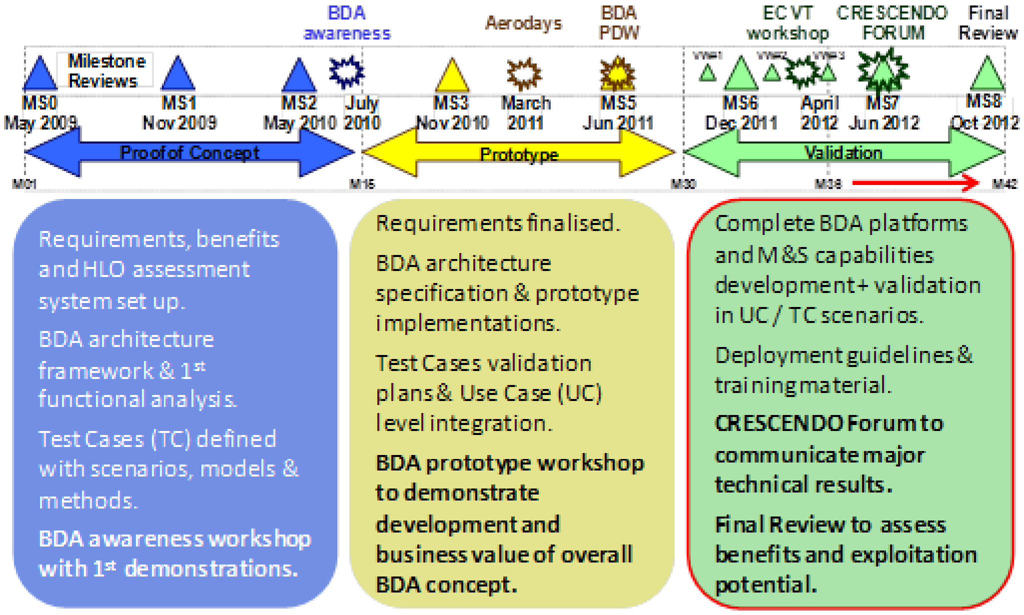


Figure 4: BDA architecture development process from Specification to Validation

Figure 5 illustrates the overall progress towards objectives, in terms of project milestones (MS0 to MS8) and the principal achievements expected in each of three major project phases defined for Proof-of-Concept (M1 to M15), Prototype (M16 to M30) and Validation (M31 to M42). For each phase, targets and criteria were set to progress the completeness and maturity of requirements definition, prototypes development and validation demonstrations of the project results.



Requirements, benefits and HLO assessment system set up.

BDA architecture framework & 1st functional analysis.

Test Cases (TC) defined with scenarios, models & methods.

BDA awareness workshop with 1st demonstrations.

Requirements finalised.

BDA architecture specification & prototype implementations.

Test Cases validation plans & Use Case (UC) level integration.

BDA prototype workshop to demonstrate development and business value of overall BDA concept.

Complete BDA platforms and M&S capabilities development + validation in UC / TC scenarios.

Deployment guidelines & training material.

CRESCENDO Forum to communicate major technical results.

Final Review to assess benefits and exploitation potential.

Figure 5: Project phases and milestones to steer progress towards expected results

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[7] “CRESCENDO Description of Work R3.0”, Annex 1 to the FP7 (2007-2013) Grant Agreement No 234344, latest version 22/06/12

3 Main Scientific & Technical results from CRESCENDO

3.1 Introduction

Seven areas of interrelated technical results from CRESCENDO are illustrated in Figure 6.

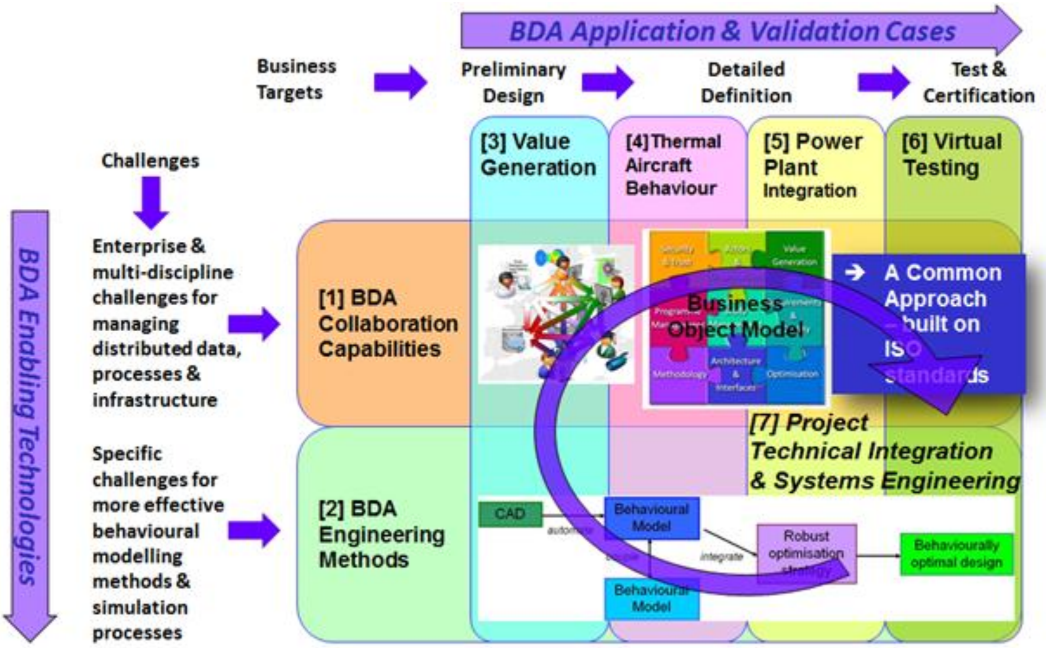


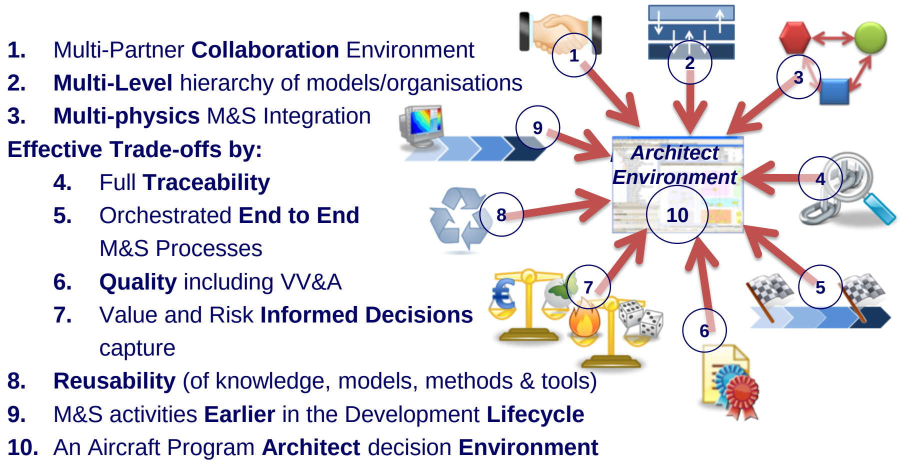
Figure 6: Seven main areas of interrelated CRESCENDO results

In order to develop foundations for the "**Behavioural Digital Aircraft**" (**BDA**), and initiate a step-change in the use of advanced Simulation Processes and Data Management (SPDM) for collaborative product development, two categories of enabling technologies were delivered:

- **BDA collaboration capabilities** address the challenges for managing distributed data, processes and infrastructure. CRESCENDO delivered a generic Business Object Model, web services and Data Exchange (DEX) specifications built on ISO standards. Interoperable SPDM platform implementations enabled data sharing and secure collaborative workflows respecting IPR. Decision environments were created for aircraft behaviour architects to orchestrate trade studies, with dashboards to monitor progress, assess quality of simulation results, and record key product development decisions.
- **BDA engineering methods** address the challenges for more effective behavioural modelling and simulation processes. CRESCENDO delivered new methods for model preparation using automated meshing and geometric reasoning techniques; surrogate and reduced order modelling; multidisciplinary optimisation and robust design strategies; advances in multi-physics coupling techniques, with some focus on thermal fluid-structure interactions, aero-thermal and aero-acoustic-vibration computational modelling.

These results can be implemented in multiple instances of interoperable **BDA platforms** and used by the multi-disciplinary modelling & simulation teams of the **BDA enterprise**, in order to manage and mature all the behavioural models & associative data needed to create a single, but distributed **BDA dataset** for a typical major aircraft development program.

Figure 7 shows the 10 key areas of innovation where benefits will be realised through the deployment & exploitation of these enabling technologies.



1. Multi-Partner **Collaboration** Environment
2. **Multi-Level** hierarchy of models/organisations
3. **Multi-physics** M&S Integration

Effective Trade-offs by:

  4. Full **Traceability**
  5. Orchestrated **End to End** M&S Processes
  6. **Quality** including VV&A
  7. Value and Risk **Informed Decisions** capture

8. **Reusability** (of knowledge, models, methods & tools)
9. M&S activities **Earlier** in the Development **Lifecycle**
10. An Aircraft Program **Architect** decision **Environment**

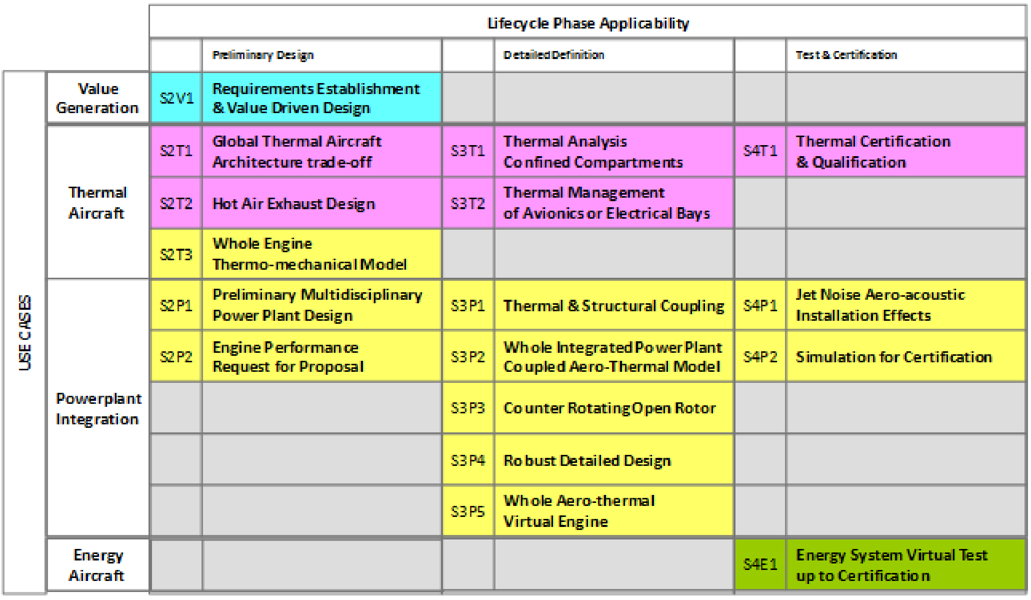
Figure 7: 10 key areas of innovation bringing benefits

In order to apply and validate these enabling technologies, the CRESCENDO project also delivered results to illustrate the ability of the BDA capabilities to be applied in the **preliminary design** and **detailed definition** phases of the product development lifecycle where the process flow is “design driven by simulation”; and also the **test and certification** phases where the process flow is “design validated by simulation”.

Four application areas were considered, referred to in CRESCENDO as the “Use Cases”: **Value Generation (VG**, **Thermal Aircraft**, **Power Plant Integration (PPI)**, and **Virtual Testing (VT)**.

These Use Cases are elements of a top-level technical process to “Perform Engineering Analysis” within a much broader set of Systems Engineering practices adopted by CRESCENDO (also see Figure 11). This forms the basis for the Use Cases Integration[8], providing a “joined-up” view of the decomposition and aggregation of the results, and illustrating the extension of the Use Cases to wider engineering application areas that are needed for developing aeronautical products.

The Use Cases are interrelated and were carried out through 17 “Test Cases”, shown in Figure 8. These were further elaborated into realistic Scenarios for demonstrating simulation-based collaborative product development across all phases of the lifecycle, and to show the maturity level and value of the enabling BDA collaboration capabilities and BDA engineering methods.



		Lifecycle Phase Applicability					
			Preliminary Design		Detailed Definition		Test & Certification
USE CASES	Value Generation	S2V1	Requirements Establishment & Value Driven Design				
	Thermal Aircraft	S2T1	Global Thermal Aircraft Architecture trade-off	S3T1	Thermal Analysis Confined Compartments	S4T1	Thermal Certification & Qualification
		S2T2	Hot Air Exhaust Design	S3T2	Thermal Management of Avionics or Electrical Bays		
		S2T3	Whole Engine Thermo-mechanical Model				
	Powerplant Integration	S2P1	Preliminary Multidisciplinary Power Plant Design	S3P1	Thermal & Structural Coupling	S4P1	Jet Noise Aero-acoustic Installation Effects
		S2P2	Engine Performance Request for Proposal	S3P2	Whole Integrated Power Plant Coupled Aero-Thermal Model	S4P2	Simulation for Certification
				S3P3	Counter Rotating Open Rotor		
				S3P4	Robust Detailed Design		
				S3P5	Whole Aero-thermal Virtual Engine		
	Energy Aircraft					S4E1	Energy System Virtual Test up to Certification

Figure 8: Use Cases and Test Cases provide realistic scenarios to validate the BDA capabilities

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[8] “Overall Use Cases Integration”, AI-UK et al, Deliverable D1.3.8

The scope for the fourth application area was different at the start of the project, initially referring to Energy Aircraft and also considering preliminary design of power plant and other aircraft systems (electrical, hydraulic, fuel) to optimise overall aircraft architecture in terms of energy (or power) sources and consumption. However, the scope became limited to focus on virtual testing for reduced dependency on physical testing to validate energy systems integration at aircraft level (S4E1 in Figure 8). Therefore, this case was considered together with other test & certification oriented cases as demonstrations for an overall Virtual Testing methodology.

Hence, the overall result in terms of potential BDA dataset coverage can be seen in Figure 9.

This shows that Value Generation (S2V1 in Figure 8) predominantly impacts the early phase of the lifecycle, where customer expectations need to be understood and translated into value drivers and technical requirements for the whole product design. Within CRESCENDO, Value Generation delivered an overall Value-Driven Design (VDD) methodology including a Value Creation Strategy (VCS) considering the collaborative context and demonstration scenarios were also linked with aspects of power plant design.

The Virtual Testing results also delivered an overall methodological approach with test cases largely positioned in the test & certification phase but also relying on results from earlier in the lifecycle. VT demonstration scenarios included integration of energy models & uncertainty analysis, and fault detection in electrical systems (S4E1); as well as simulation for thermal equipment qualification (S4T1) and simulation supporting certification of power plant (S4P2); and more accurate prediction methods for installed jet noise in take-off conditions enabling earlier ‘virtual testing’ of configurations not yet physically existing (S4P1).

Both Thermal Aircraft behaviour and Power Plant Integration application cases cover all phases of the lifecycle. There is also some overlap since several PPI test cases also focus on thermal modelling, for example the whole engine thermo-mechanical model in S2T3; the integration of thermal-structural models in S3P1; and aero-thermal modelling in S3P2 and S3P5.

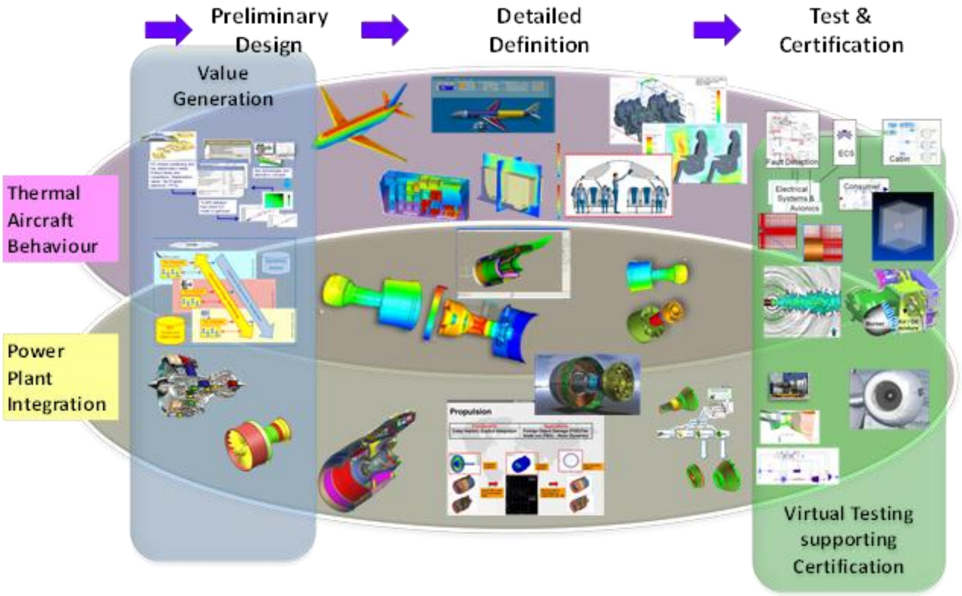

Figure 9: Behavioural Digital Aircraft Dataset coverage by CRESCENDO application cases

For the collective demonstration and validation of the results, a so-called **Federated Validation Platform** (FVP[9]) was progressively built during the course of the project. This started in the Proof-of-Concept and Prototype phases of CRESCENDO, with largely stand-alone implementations by individual partners, demonstrated at the BDA awareness workshop (June 2010), but made significant progress for the Prototypes Demonstration Workshop (June 2011). A major advance, from the Prototype to Validation phase of CRESCENDO, was to establish a more connected network of industry labs between various partner sites, see Figure 10.

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[9] “Federated Validation Platform Implementation”, NLR et al, Consortium Confidential Deliverable D5.1.7

The FVP allowed the installation and functional verification of the prototype solutions, and was successfully used to validate the application of the BDA collaboration capabilities and engineering methods by running the various test cases' scenario processes in more realistic environments. This was a main focus of activity to prepare the CRESCENDO Forum (June 2012).

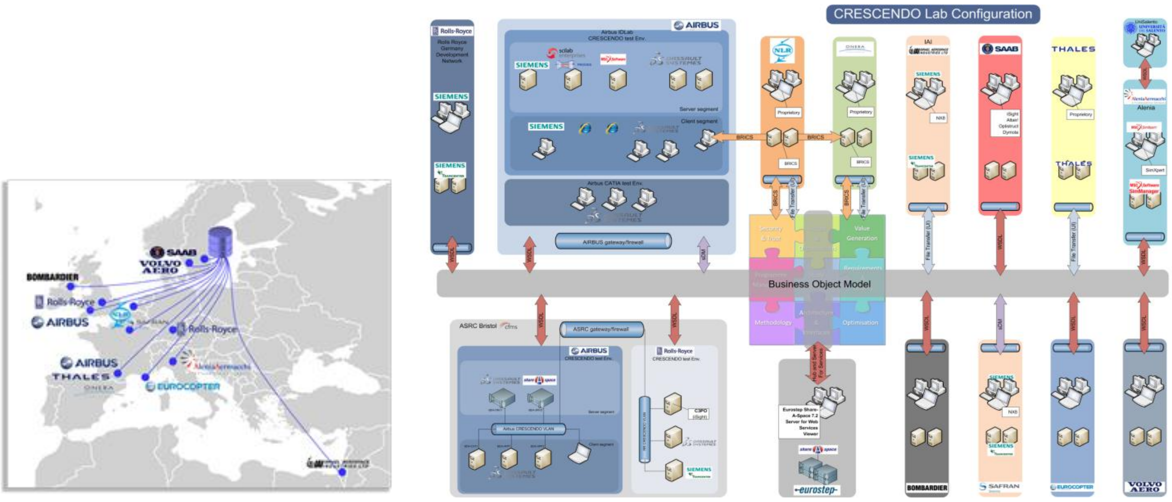

Figure 10: CRESCENDO Industry lab network and Federated Validation Platform

The following chapters highlight a selection of the technical achievements, to provide further insight into each of the interrelated areas of results introduced in this chapter with Figure 6, and listed below with the relevant result "Id" references used in the CRESCENDO Results Catalogue (chapter 4.8 and Appendix C).

- **BDA Collaboration Capabilities**: R14, R15, R20, R26, R35, R38, R40, R44, R48, R50, R51, R52, R53, R54, R58, R62, R75, R78, R82, R90, R99, R101, **R102**, **R103**, R104, R105. Related results for the CRESCENDO standardisation strategy are also derived in terms of recommendations [**R69**] and preliminary DEX specifications [**R106**] that are further described in chapter 4.5 of this report.
- **BDA Engineering Methods**: R1, R2, R3, R4, R11, R12, R13, R14, R16, R17, R20, R21, R22, R23, R24, R25, R27, R28, R29, R30, R31, R32, R33, R36, R37, R45, R46, R47, R49, R61, R63, R64, R65, R75, R76, R79, R80, R81, R82, R85, R86, R91, R92, R94, R96, R97, R100, R108.
- **Value Generation** methods & tools: R7, R8, R9, R18, R48, R59, R60, R61. Aircraft-level, as well as Power Plant system & component examples, were used extensively by the VG results and two specific results [R7 & R61] were coupled with a demonstration scenario for the Preliminary Multidisciplinary Power Plant Design test case (S2P1).
- **Thermal Aircraft** behaviour application results: R16, R17, R25, R29, R45, R49, R52, R53, R58, R63, R64, R75, R76, R78, R82, R90, R91, R92, R94, R96, R101
- **Power Plant Integration** application results: R1, R2, R3, R4, R5, R7, R11, R12, R13, R14, R15, R16, R17, R19, R20, R22, R23, R24, R27, R28, R29, R30, R31, R32, R33, R35, R36, R37, R38, R44, R46, R47, R51, R52, R53, R58, R61, R62, R78, R79, R81, R82, R86, R97, R99, R100, R104, R105, R108
- **Virtual Testing** methods: R2, R19, R36, R37, R51, R65, R80, R85, R94, R98, R99, R100
- Overall project technical integration and systems engineering results: R57, R70, R74, R107. Aspects of these are included more appropriately in chapter 4 of this report, describing potential impact, dissemination and exploitation.

VG, Thermal, PPI and VT results have of course used and influenced others, notably the BDA Business Object Model [**R102**], web services [**R103**], and subsequent DEX standardisation proposal [**R106**], as well as many BDA Engineering Methods.

3.2 BDA Collaboration Capabilities for managing distributed data, processes and infrastructure

The BDA Collaboration Capabilities results have been developed to support teams within an organisation or partners across an extended enterprise. These results enable more successful collaboration in the following ways:

- How to manage distributed data. In particular, making this data available at an Architects level. This means rapid access to many different sources of data that are brought together to enable the architect to make informed business and technical decisions. This data includes the record of who did what, when, where, how and why.
- How to manage distributed processes. In particular, delivering the right data at the right time for every step of the process, and coping with the fact that execution is asynchronous, occurs at different locations and retrieves inputs from other locations. Equally, we need flexible processes that can be configured dynamically to solve a changing problem.
- How to manage distributed infrastructures. In particular, we need to improve the ability of organisations to connect to, and disconnect from, a collaboration process without having to modify the other members. At the same time the infrastructure must ensure the security of data, assets and resources over heterogeneous solutions as each participating member controls their own security and access policies.

The following paragraphs summarise the main results related to BDA Collaboration Capabilities.

3.2.1 BDA Architecture Specification, Business Object Model (BOM) and Deployment Guidelines

One key result **[R102]** of CRESCENDO is a robust Behavioural Digital Aircraft architecture specification[10]. As shown in Figure 11 this comprises a set of models (Business Concept, Business Object, and Data) and information services that conform to the BDA Architecture Framework[11] established early in the project and inspired by Systems Engineering principles[12]. The overall process to develop and validate the BDA architecture was shown previously in Figure 4.

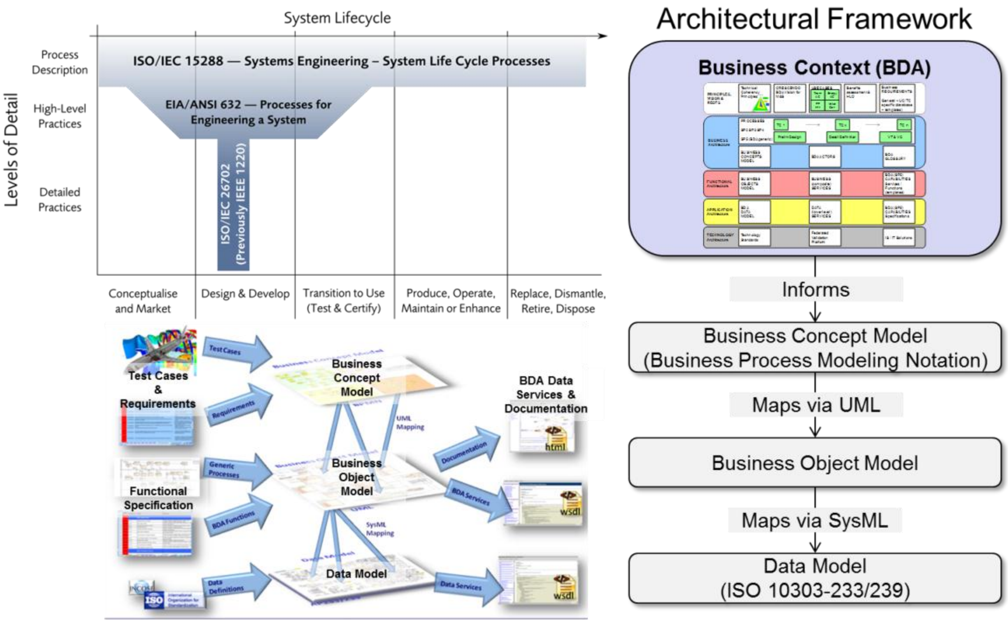

Figure 11: A Systems Engineering Framework for the BDA Architecture

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[10] "BDA Architecture specification", AI-UK et al, Public Deliverable D5.1.2 with associated other materials

[11] "BDA Architecture Framework", AI-UK et al, Deliverable D5.1.1

[12] "ISO 15288: Systems Engineering — System Life Cycle Processes" establishes a framework for describing the life cycle of systems created by humans; "ANSI/EIA 632: Processes for Engineering a System" provides an integrated set of fundamental processes for the engineering of a system; "ISO/IEC 26702" defines interdisciplinary tasks needed to transform customer needs & requirements into a product.

The Business Concept Model defines information at a business level and is expressed in language used by domain experts (i.e. the end users). This does not provide sufficient detail for implementation but provides the requirements for the information and semantics that need to be represented by the Business Object Model and used by the BDA services.

The Business Object Model (BOM) is at the heart of the BDA architecture. The BDA-BOM provides a common language for collaboration that makes it possible for partners to capture the cross-organisation traceability of product and supporting information across the end-to-end development lifecycle, so allowing informed decisions based on a wealth of knowledge. In effect, it governs nine main aspects of the collaborative simulation process & data management effort: Security and Trust; Actors and Organisation; Programme Management; Study Management; Architecture and Interfaces; Methodology; Requirements and Quality; Value Generation; and Optimisation.

Figure 12 presents a simplified view of the BDA Business Object Model content defined in UML[13]. Both the Business Concept Model and Business Object Model were created using Enterprise Architect[14] but as this is not a commonly available tool, the complete information is also packaged and made available as a set of HTML pages, or via an XMI file. However, all formats assume an understanding of UML.

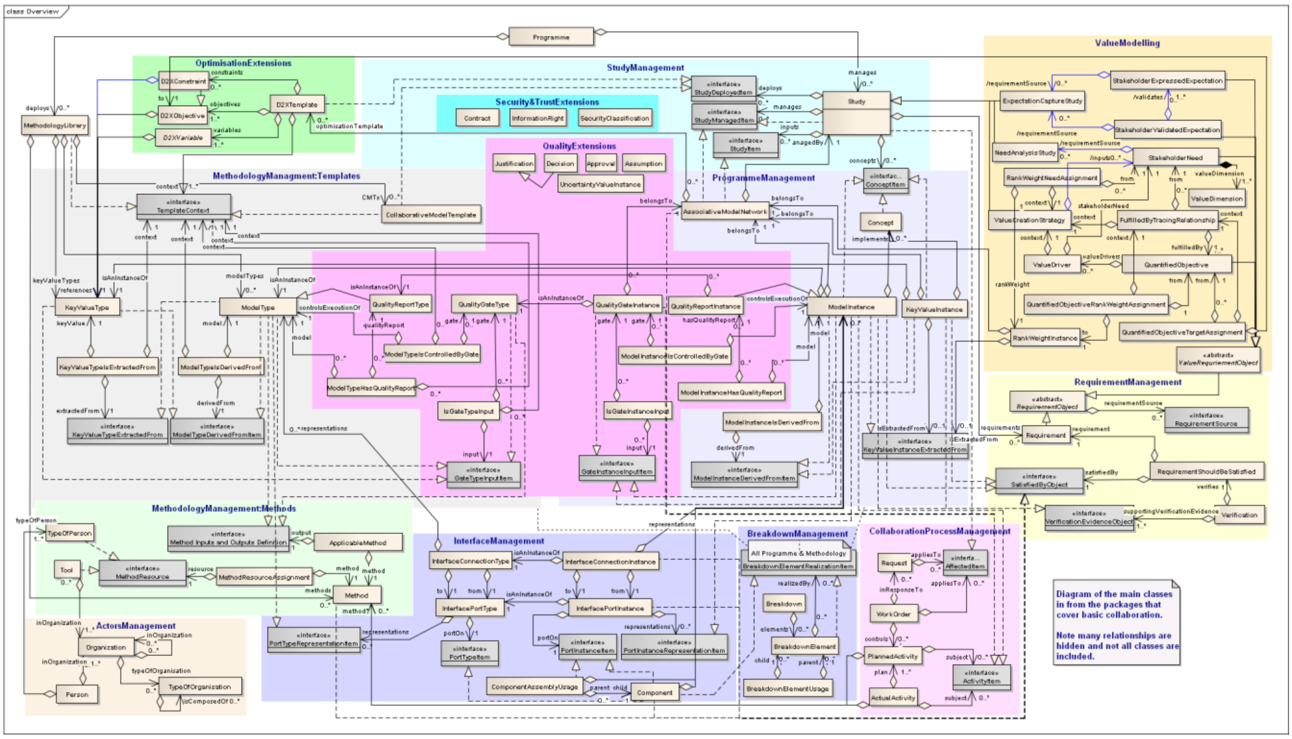

Figure 12: BDA Business Object Model – simplified view

As shown schematically in Figure 13, the common language expressed in the BDA-BOM is built on international standards ISO 10303-233 (Systems Engineering) and ISO 10303-239 (Product Life Cycle Support). It provides a communication mechanism to systems outside of the BDA platforms environment because there are already tools and implementations available that are based on these standards. Additionally, it provides an archive format for the BDA dataset.

The BDA Data Services, as defined in the BDA architecture, are implementation independent. Most implementations use web services, and these require a client that calls the services and a server that responds to the client's calls.

The result **[R103]** is the complete set of web services specifications[15] using WSDL and XSD.

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[13] Unified Modeling Language, see http://uml.org/

[14] See http://sparxsystems.com.au/

[15] "Enterprise Collaboration Architectures, Capabilities and Standards Specification Report", GKNAES et al, Deliverable D5.5.3

There was one server-side implementation delivered (for the duration of CRESCENDO) using the Share-A-space™ collaborative hub from Eurostep. Multiple clients were also written to call and access the server for the FVP used to support the test cases demonstration scenarios, listed as follows per software system and partner identifier: BRICS (NLR); CODA Excel client (USOTON); Isight client (ENGS & DS); SimManager clients (MSC & USALENTO); Teamcenter client (SIEMENS); and a Java web services client to integrate PySimulator (DLR).

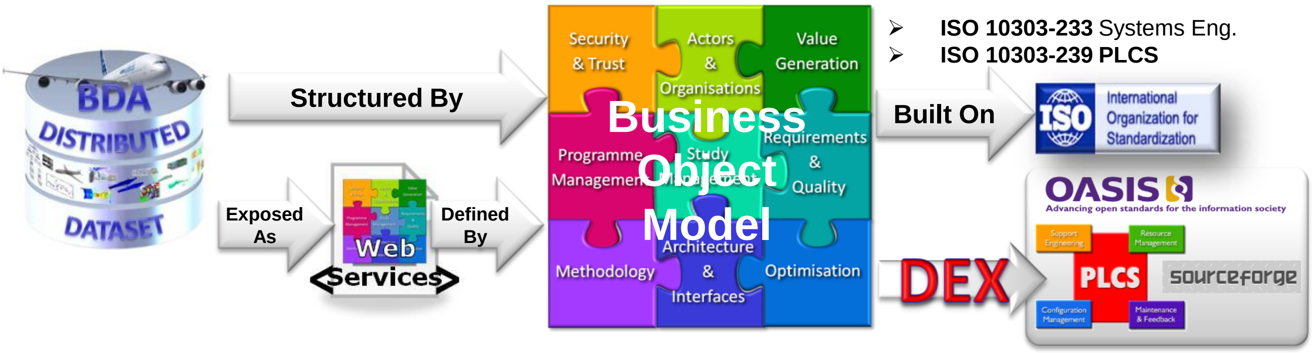

Figure 13: BDA Business Object Model provides the "common language" for a Collaboration Standard

The deployment of the BDA architecture in industry implies a significant change of behaviour, and supporting processes for companies. Therefore a set of guidelines[16] have also been written to provide some practical considerations for deployment and to outline the related training material available as part of the BDA e-Learning portal (see chapter 4.8). These include both an Executive and Implementers guide to the BDA architecture specification, as well as an introduction to the BDA web services and Enterprise Collaboration capabilities.

For the BDA Architecture to persist after the end of CRESCENDO, a specific interpretation of ISO 10303-233/239 was developed for the BDA Business Object Model, using the OASIS PLCS DEX approach (see chapter 4.5). Consequently, this standardisation proposal can be used by both software providers and industrial partners to utilise the work of the CRESCENDO project, whilst having the opportunity to develop it further.

A separate assessment[17] of the maturity and completeness of the BDA architecture was also conducted. This concluded that the BDA Architecture Framework was effective and that the specification was successfully applied to support CRESCENDO test case demonstrations, although some recommendations to improve the accessibility of the Business Object Model and associated web services were also identified.

The conclusions[18] are that CRESCENDO has successfully demonstrated effective enterprise collaboration using the defined BDA-BOM together with the derived web services, and that both implementers and users have gained valuable experience from the demonstrations.

Main partners involved in developing these results: AI-UK, EUROSTEP, EADS & GKNAES, with AI-F, AFNOR, ALENIA, DS & ENGS, DLR, EADS, ECPTR, Fujitsu, LMS, MSC, NLR, RR-UK, SAMTECH, SIEMENS, SNECMA, UNINOVA, USOTON, VINCI.

3.2.2 Enabling secure collaboration and process execution in cross-enterprise workflows

The ability to support collaborative simulation relates to several of the key function areas[19] specified for BDA platforms simulation capability i.e. flexible workflow, traceability & re-usability, and advanced interoperability.

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[16] "BDA Architecture and capabilities deployment and training guidelines", ALENIA et al, Public Deliverable D5.1.5

[17] "BDA Architecture validation and compliance with requirements", RR-UK et al, Consortium Confidential Deliverable D5.1.4

[18] "Enterprise Collaboration Capabilities, Services and Standards Implementation Report", Eurostep et al, Deliverable D5.5.4

[19] "BDA Simulation Factory Specification and Implementation", NLR et al, CRESCENDO Deliverable D5.3.3

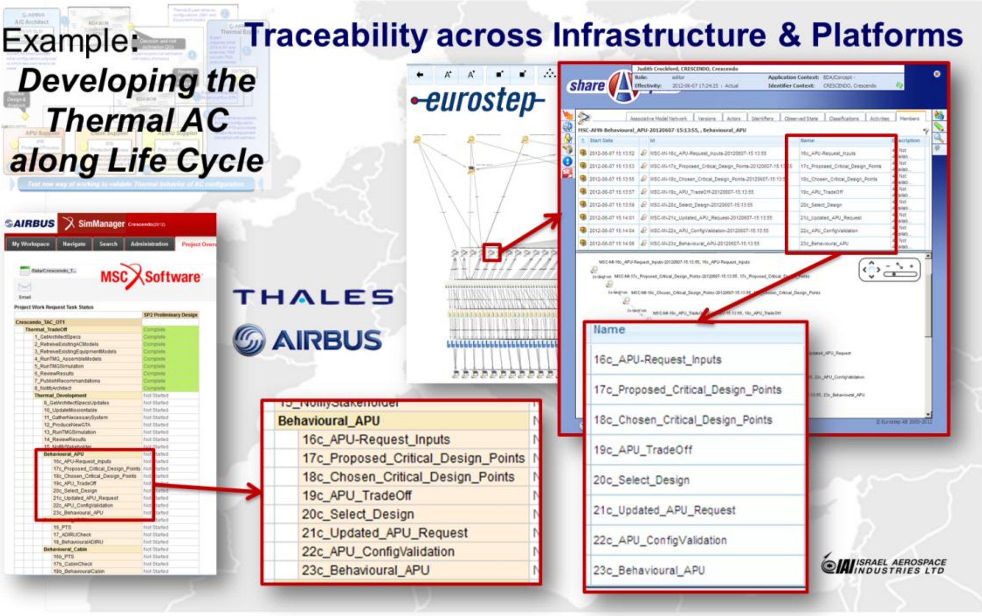
To enable the set-up of a secure collaboration [**R52**], three key mechanisms and relevant areas (as seen in Figure 13) of the BDA Business Object Model were identified.

Collaboration Initialisation: This has to satisfy the need for partners to join & leave the collaboration quickly & easily, while respecting their own company's IT security policies. The relevant BDA-BOM areas are "Security & Trust" (for example objects describing contracts, security classifications and access rights) and "Actors & Organisations".

Collaboration Operation: Key factors here are providing trusted people with appropriate access to distributed data, maintaining traceability across infrastructure & platforms, and protecting Intellectual Property.

- All the BDA Business Objects could be used to access and manage distributed BDA datasets; key areas demonstrated were "Study Management" (for example objects describing the Study itself e.g. 'engine trade study', the Study Concept to be investigated e.g. 'engine configurations', the Study Objective e.g. 'optimise performance'); "Programme Management" (e.g. objects describing Model Instances and Key Values, and the definition of their relationships in an Associative Model Network); and "Requirements & Quality" (e.g. the elements for verification, validation and acceptance, and recording assumptions, approvals, decisions).
- Traceability was demonstrated with common data held by various software used in different roles. For example, Share-A-space (Eurostep) acting as a collaboration hub; SimManager (MSC) and ENOVIA (DS) supporting the architect view; SimManager (again) and TeamCenter (Siemens) being used by model or simulation data supplier.
- The first example in Figure 14 is from a Thermal Aircraft test case and shows Model Network data defined in SimManager. This is then (one of many) being published to the collaboration hub, where the same data is then visible. The second example in Figure 15 is from a PPI test case. This shows data in the collaboration hub that is traceable to a template first defined in ENOVIA (DS) that describes a sequence of activities i.e. how the study is to be done.

Collaboration Termination: The main concerns here are how to archive individual pieces of data (e.g. an old baseline), and how to archive the entire dataset from a collaboration activity. The steps to consider are first deciding what to archive; then transfer of ownership from the original organisation to the archive organisation; modification of access rights if needed; and ultimately storage as standards-based data for long term archival.



Traceability across Infrastructure & Platforms

Example: Developing the Thermal AC along Life Cycle

Behavioural_APU
16c_APU-Request_Inputs
17c_Proposed_Critical_Design_Points
18c_Chosen_Critical_Design_Points
19c_APU_TradeOff
20c_Select_Design
21c_Updated_APU_Request
22c_APU_ConfigValidation
23c_Behavioural_APU

Name
16c_APU-Request_Inputs
17c_Proposed_Critical_Design_Points
18c_Chosen_Critical_Design_Points
19c_APU_TradeOff
20c_Select_Design
21c_Updated_APU_Request
22c_APU_ConfigValidation
23c_Behavioural_APU

Figure 14: Enabling Collaboration Operation with Traceability – example with model network data in MSC SimManager

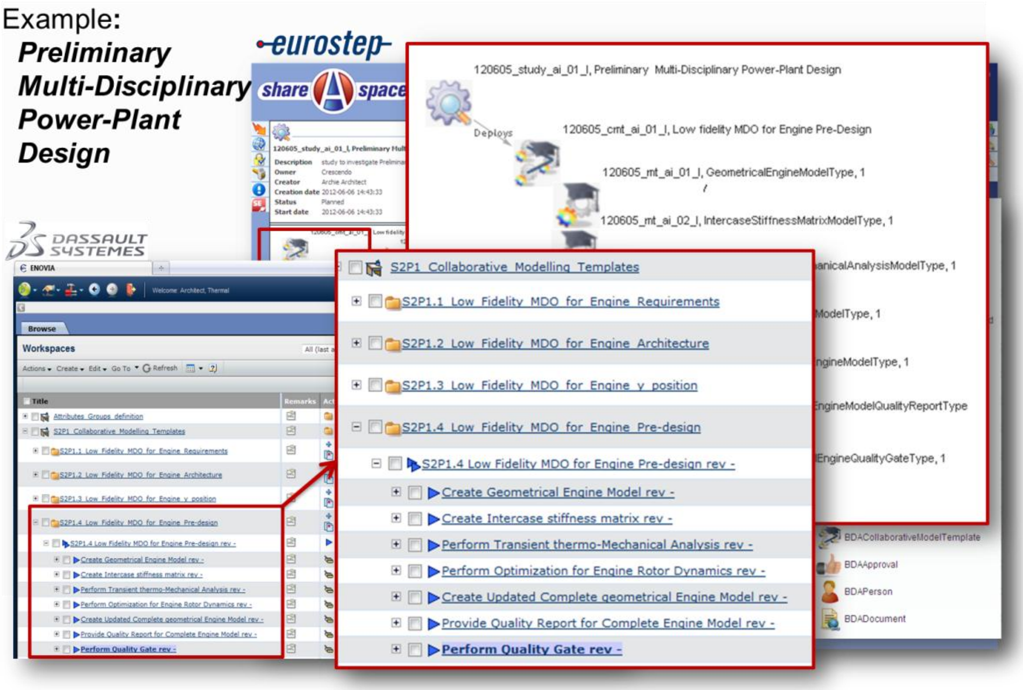


Figure 15: Enabling Collaboration Operation with Traceability
– example with Study template data in DS ENOVIA

Flexible workflows for simulation process execution can be categorized in many different ways. Two characterisations were observed[20] in CRESCENDO and proposed as helpful for determining the best strategy to implement and execute the workflows:

1. How **control** of one element in the workflow is passed to the next and what triggers the execution of the next part. Two types of workflow are considered: **event-driven** or **process-driven**.
2. How often the execution of the workflows is iterated. **Low** frequency workflows are only executed one or very few times; **medium** frequency workflows a few dozens of times; and **high frequency** workflows at least some hundreds of times.

For example (see Figure 16), the Global Thermal Aircraft (GTA) test case (S2T1) was observed to implement several event-driven and low frequency workflows. Here each activity can consist of interactive work using a simulation tool or can be a review meeting, and the exact sequencing of the steps in the workflow is often not known in advance. In contrast, for process-driven workflows, each execution detail is known before the process starts, and so these can be executed in an automated fashion.

In CRESCENDO, it was observed that process-driven workflows were implemented in the PPI demonstration scenarios such as CREDO[21] (in S3P4). This is an industrial example of a high frequency and process-driven workflow in the extended enterprise. In CRESCENDO, the partners involved typically used the SIMULIA Execution Engine (SEE) in addition to the process integration software Isight (both solutions developed by DS) for this type of problem **[R105]**. For the Low Pressure Turbine (LPT) design within CREDO, a specific web service was developed by MTU to connect to the other partners via the BDA server. In some of the implemented test cases, an activity in a larger event-driven workflow executes a process driven workflow, so both types can coexist.

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[20] "Executing optimization processes in the extended enterprise", by R. Parchem (RR-D) & H. Wenzel (ENGS), accepted for NAFEMS World Congress, Salzburg, 2013

[21] "Collaborative Robust Engineering Design Optimisation", by R. Parchem & P. Flassig (RR-D) with H. Wenzel (ENGS), accepted for SIMULIA Community Conference, Vienna, 2013

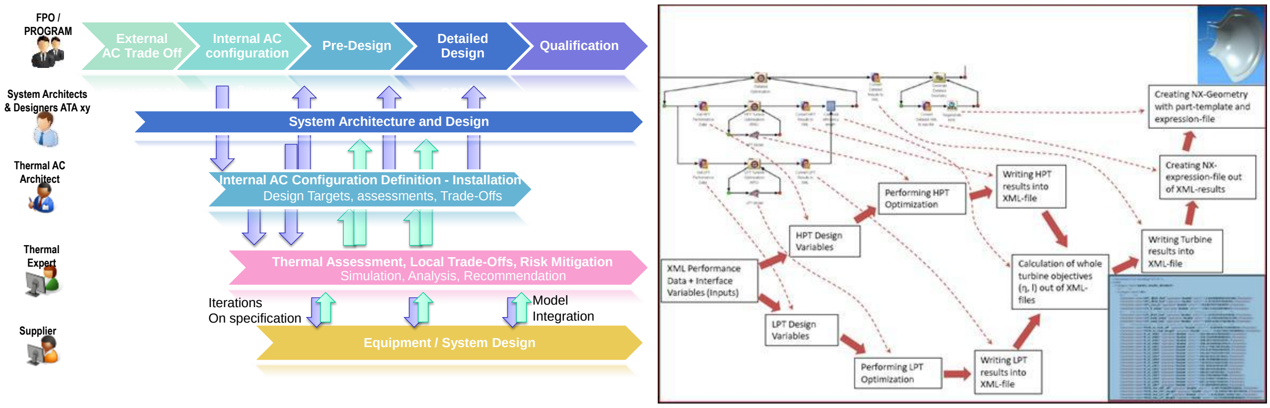

Figure 16: Examples of event-driven (Thermal A/C) and process-driven (CREDO) workflows

Medium frequency workflows may become tedious to run interactively and are therefore often process-driven. For example see the middle picture in Figure 17 with AirCADia (UCRAN) and Isight (DS) executing at different locations and coupled through the BRICS middleware further developed by NLR during CRESCENDO. However, security constraints may arise with automatic execution of remote activities.

The BRICS solution (NLR) uses the notion of "tool stubs" to transform a single-partner simulation workflow into a true multi-partner or cross-enterprise collaborative simulation workflow **[R51]**. Effectively, a wrapper is placed around tools or parts of the overall workflow so they may be executed by remote users and to overcome IT security constraints & trust rules that restrict access by other computers, networks or companies. In this way, BRICS caters for secured exchange of input / output data via a shared data server; notification of remote engineers; either manual or automated execution arranged under responsibility of the remote engineer; and single runs as well as iterative optimisation loops[22].

This solution was demonstrated in the CRESCENDO test cases i.e. preliminary multidisciplinary power plant design (S2P1, shown in Figure 17) and energy system virtual test (S4E1) scenarios.

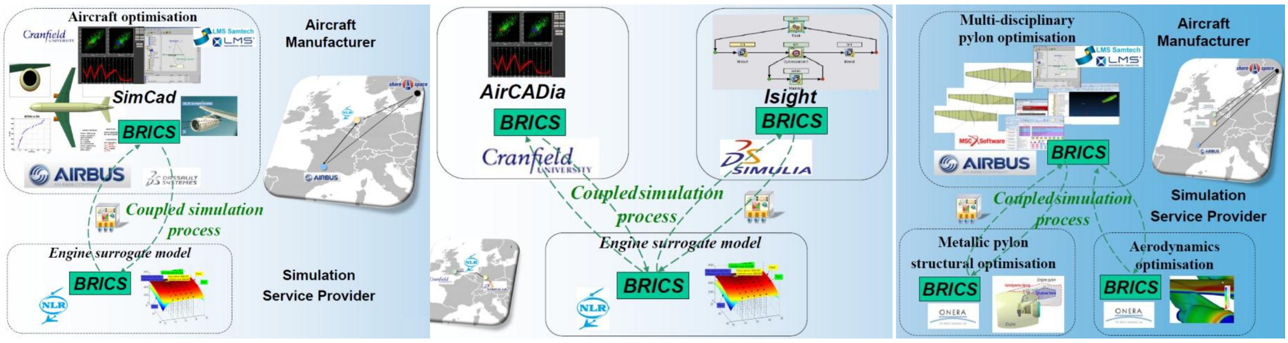

Figure 17: Using BRICS to support secure execution of cross-enterprise collaborative workflow

In addition, UCRAN have developed a way **[R104]** to support the dynamic (re)configuration of simulation workflows. It offers a workbench for assembling and establishing the optimal execution sequence for a given set of computational models, considered as black-boxes. This latter requirement arises from the need to protect IPR of collaborating partners, who may supply certified executables (DLLs) to other partners, but not necessarily the source code. For this, particular attention was given to the interactive reconfiguration / reversal of specific models from the Airbus aircraft sizing code (SIMCAD), and the possibility of exporting simulation workflows in a neutral representation[23] to other partners (e.g. using Isight from DS).

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[22] "Mastering Restricted Network Access in Aeronautic Collaborative Engineering across Organizational Boundaries", by E.H. Baalbergen (NLR) et al, at PDT Europe, The Hague, 2012

[23] "Neutral Description and Exchange of Design Computational Workflows", by A.C. Gondhalekar, M.D. Guenov (UCRAN) et al, at International Conference on Engineering Design (ICED), Copenhagen, 2011

Finally, UCAM have implemented the Change Propagation in Workflows (CPiW) technique their Cambridge Advanced Modeller tool. This provides a first application of change propagation techniques into the process domain of workflows. It allows analysis of scenarios (e.g. trade-off studies, implementation of value creation strategies) before work is initiated, and can reveal knock-on impacts of choices in terms of tasks and resources affected. This enables stakeholders to make earlier and better informed risk and value decisions. In CRESCENDO, CPiW was applied in several areas, including Thermal, PPI and Value Generation.

Main partners involved in developing these results: GKNAES, AI-UK, AI-F, EUROSTEP, DS & ENGS, MSC, MTU, NLR, RR-D, SIEMENS, UCRAN, UCAM.

3.2.3 Behaviour Architect capabilities

The role of the Behaviour Architect [**R40**] is to make decisions affecting the optimisation of aircraft behaviour (aerodynamic, acoustic, structural, thermal and so on), performing global trade-offs and sensitivity analyses, to be able to predict confidently that aircraft performance requirements will be satisfied through to certification. The CRESCENDO results [**R53,** illustrated in Figure 18] provide capabilities[24] for Behaviour Architects to work effectively with the various discipline experts, to aid the decision-making with dashboards and visualisation of results, and to orchestrate the architecture trade-off and behavioural modelling & simulation processes.

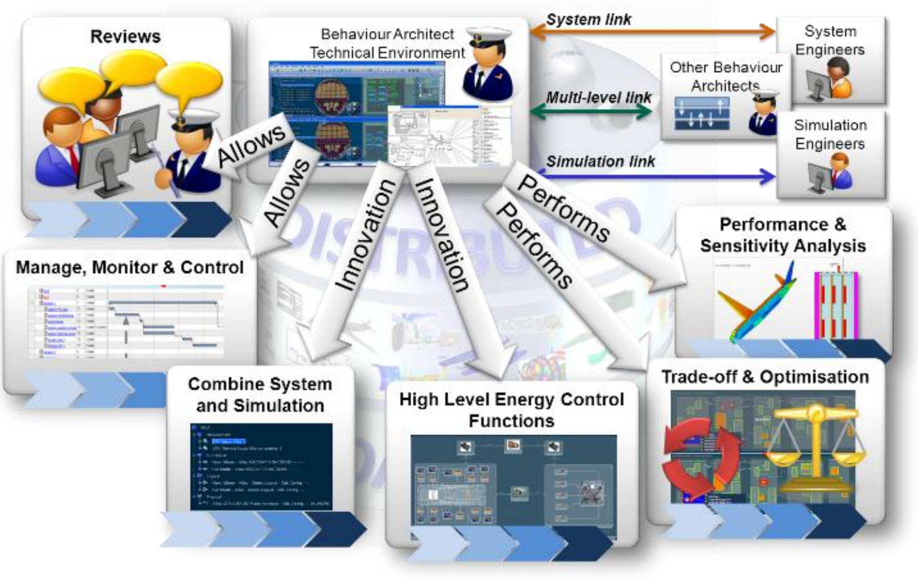

Figure 18: Schematic view of capabilities to support Behaviour Architects

Within CRESCENDO, this environment was principally illustrated with solutions from DS (Enovia, RFLP), LMS (Imagine.Lab) specifically for the integration of systems architecture behaviour (e.g. avionics), and MSC (SimManager) in a thermal architecture context [**R58** ref S2T1 test case]; as well as other demonstrations for collaborative approaches to manage design convergence between airframe & engine manufacturers and to manage pylon trade-off studies [**R62 & R35** ref S2P1 test case]; distributed simulation for power plant thermal integration [**R82** ref S3P2 test case]; and an integrator environment to support the product definition [**R15** ref S3P1 test case].

CRESCENDO advances in the important areas of Simulation Quality[25] assessment are only briefly summarised here. Verification, Validation and Acceptance (**VV&A**) processes capture quality related information that can be attached to modelling & simulation assets as evidence of their correctness, validity and utility i.e. to ensure that behavioural models are fit-for-purpose. The BDA BOM includes specific quality related objects such as Approval, Quality Gate and Quality Report. The use of statistical techniques, e.g. probabilistic distributions and uncertainties management, helps to quantify risks and ensure confidence in simulation results at appropriate

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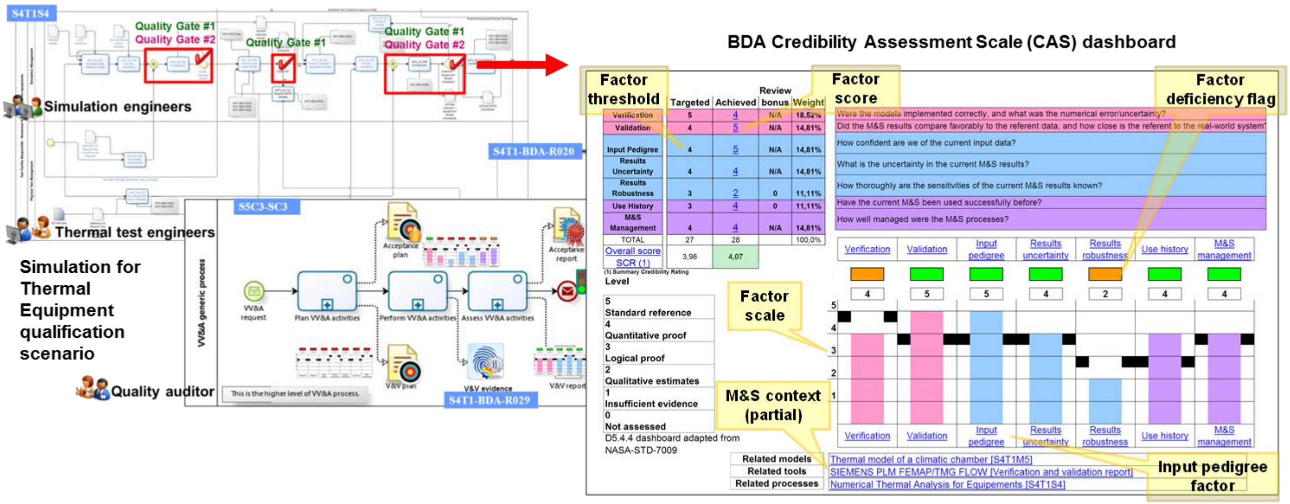
[24] "BDA Model Store Prototype Dossier", EADS et al, Deliverable D5.2.5

[25] "BDA Quality Laboratory Prototype", EADS et al, Deliverable D5.4.4

decision points. Methods to improve traceability and comparison between real test and simulation results have been demonstrated to support virtual testing and certification (also see chapter 0). Knowledge management techniques to model and analyse collaborative decisions made by experts[26] have been developed [**R101**]. Finally, visualisation of quality assessment data in reports or on dashboards has been shown in several test cases, to make key information visible to decision makers at each phase of the development lifecycle.

One result [**R54**] that attracted attention is the BDA adaptation of the Credibility Assessment Scale (CAS) dashboard[27] shown in Figure 19, based on NASA STD 7009 to include a range of quality indicators more specific for aeronautics industry and visualise Simulation Quality metadata to support decision making at quality review gates for example.



	Targeted	Achieved	Review bonus	Weight	
Verification	5	4	N/A	18,52%	Were the models implemented correctly, and what was the numerical error/uncertainty?
Validation	4	5	N/A	14,81%	Did the M&S results compare favorably to the referent data, and how close is the referent to the real-world system?
Input Pedigree	4	5	N/A	14,81%	How confident are we of the current input data?
Results Uncertainty	4	4	N/A	14,81%	What is the uncertainty in the current M&S results?
Results Robustness	3	2	0	11,11%	How thoroughly are the sensitivities of the current M&S results known?
Use History	3	4	0	11,11%	Have the current M&S been used successfully before?
M&S Management	4	4	N/A	14,81%	How well managed were the M&S processes?
TOTAL	27	28		100,0%	
Overall score SCR (1)	3,96	4,07			

(1) Summary Credibility Rating

Level	
5	Standard reference
4	Quantitative proof
3	Logical proof
2	Qualitative estimates
1	Insufficient evidence
0	Not assessed

D5.4.4 dashboard adapted from NASA-STD-7009

Verification	Validation	Input pedigree	Results uncertainty	Results robustness	Use history	M&S management
🟧	🟩	🟩	🟩	🟧	🟩	🟩
4	5	5	4	2	4	4

Related models	Thermal model of a climatic chamber [S4T1M5]
Related tools	SIEMENS PLM FEMAP/TMG FLOW [Verification and validation report]
Related processes	Numerical Thermal Analysis for Equipements [S4T1S4]

Figure 19: Credibility Assessment Scale dashboard applied in Thermal Equipment Qualification scenario

Furthermore, awareness and training materials dedicated to these results have been created within the Behaviour Architect, Simulation Integrator, and Simulation Quality course modules of the BDA e-Learning portal (see chapter 4.8).

Main partners involved in developing these results: EADS, AI-UK, AI-F, DS, ECPTR, ISPACE, LMS, MSC, ONERA, SIEMENS, VINCI

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[26] "Collaborative modelling: organize, report and understand an experts' group debate", by T. Polacsek & L. Cholvy (ONERA), at 4th European Conference for Aerospace Sciences (EUCASS), Saint Petersburg, Russia, 2011

[27] "Towards Application of NASA Standard for Models and Simulations in Aircraft Design Process"; by L. Vincent (EADS) et al, at International Space System Engineering Conference DASIA, Dubrovnik 2012

3.3 BDA Engineering Methods for Modelling & Simulation

The BDA Engineering Methods results (illustrated schematically in Figure 20) provide innovative modelling and simulation capabilities to generate the behavioural data efficiently, effectively, and with appropriate quality for the preliminary design[28], detailed definition[29] and test & certification[30] phases of the product development lifecycle. In the test cases supporting Thermal Aircraft behaviour, Power Plant Integration or Virtual Test, these results demonstrated:

- Automation of manual, time consuming CAD geometry idealisation and mesh generation e.g. for fluid applications and for structural applications;
- Effective coupling methods between various behavioural models generated from different domains such as aero-thermal, aero-acoustic, vibro-acoustic, fluid-structure, thermo-mechanical, and electric-structural couplings;
- Surrogate and compact modelling methods for earlier and more rapid analysis with models that respect Intellectual Property Rights (IPR);
- Efficient collaborative optimisation strategies, as applied in the business test cases context, taking into account the possibilities to couple models;
- And robust design optimisation methods to effectively handle uncertainties during optimisation.

A selection of these results are summarised in the following paragraphs.

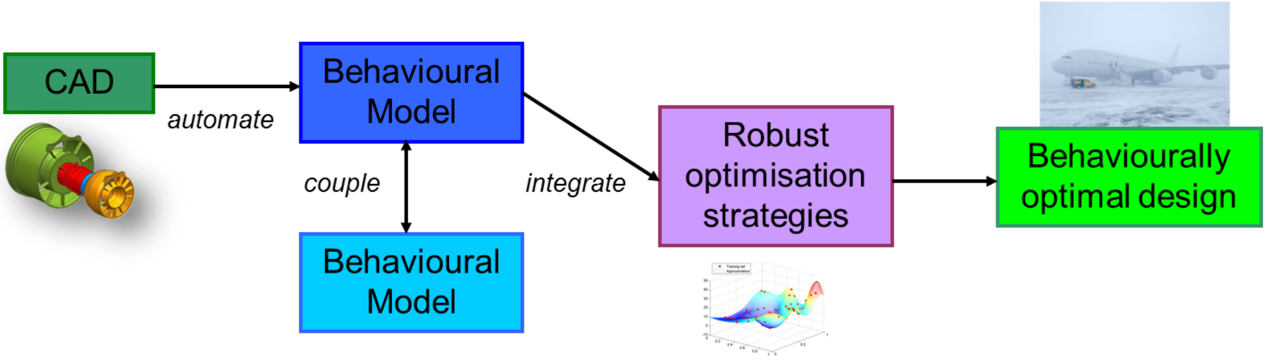

Figure 20: From CAD to behaviourally optimal design using innovative BDA engineering methods

3.3.1 Efficient geometry preparation and meshing techniques

The objective for engineering analysts is to be able to focus on the analysis (e.g. FEA or CFD), rather than spending significant time and effort to prepare geometry with such activities as 3D CAD model de-featuring and clean-up. The geometry required by **CFD analysts** is the fluid domain (i.e. typically the void within a part), not the part geometry itself. Two approaches were studied by AI-UK (with support from Airbus Engineering Centre India) and Siemens for an Airbus wing fuel tank volume **[R63]** in the test case (S3T1), as shown in Figure 21. The techniques were also applied successfully for a complex helicopter engine geometry **[R16]** provided by Eurocopter and Turbomeca in the context of the WIPCATM test case (S3P2).

This result indicates a **highly improved efficiency for CFD analysis, reducing geometry preparation & meshing time from weeks to days**.

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[28] E.g. reference “Test case links between models”, DLR et al, Deliverable D2.3.3; and “Trade off studies in the preliminary design phase”, AI-F et al, Deliverable D2.4.2; and “Dissemination of the preliminary MD demonstration results at the Forum”, USALENTO et al, Deliverable D2.4.3

[29] E.g. reference “Capabilities for setting up a model for the detailed design phase and their contribution to demonstrations”, SNECMA et al, Deliverable D3.3.5; and “Integration of Optimisation and Robust Design with the BDA, including Test Case Results”, RR-D et al, Deliverable D3.4.4

[30] E.g. reference “SP4 Demonstration results synthesis”; SAAB et al, Deliverable D4.1.2; “VT&VC Test cases demonstration and evaluation”, ECPTR et al, Deliverable D4.4.4

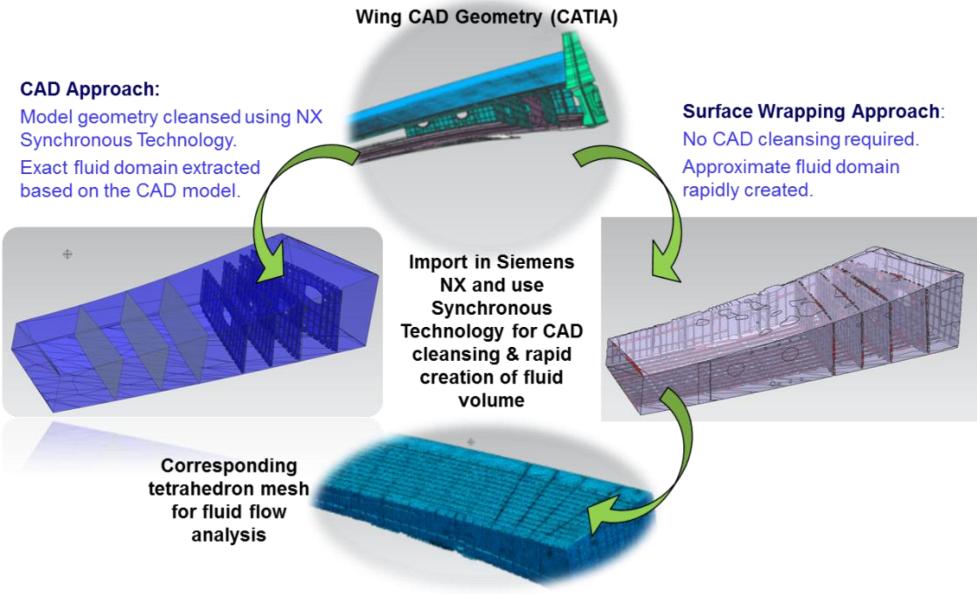
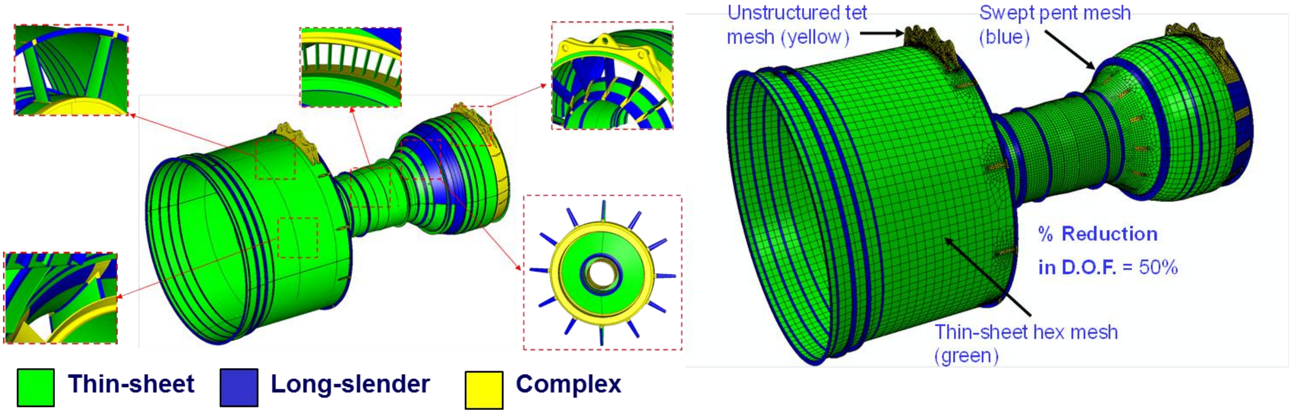


Figure 21: Rapid extraction of fluid domain from CAD geometry

Two innovative **geometric reasoning techniques** [**R29**] for automated decomposition of CAD models were developed by TranscenData (TRN) and Queen's University Belfast (UBELFAST)[31]:

- The TranscenData CADfix tool successfully decomposes complex geometries into thick and thin sub-regions. The 3D medial object in CADfix has been significantly advanced to **automatically** detect and separate a greater number of **thin-sheet regions** suitable for structured meshing, and for more complete and complex CAD models. The CRESCENDO improvements will be available in CADfix R9.0.
- Algorithms developed by UBELFAST have been integrated in CADfix, and are used to automatically detect and separate **long-slender regions** from the remaining complex 3D regions.

The result is a model sub-divided into an assembly of thin-sheet, long-slender, and residual complex solids. This is illustrated in Figure 22, for the application to a **whole engine model Finite Element (FE) analysis** with RR-UK [**R46** & **R97** as part of reference S2T3 test case], where previously only a partial engine geometry decomposition was possible.



Automatic Decomposition into an assembly of sub-regions

An efficient semi-structured mesh of the whole engine assembly can be generated

Figure 22: Geometry reasoning for automated CAD decomposition and efficient meshing

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[31] "Automatic Decomposition and Efficient Semi-Structured Meshing of Complex Solids", by J.E. Maken (UBELFAST) et al, Proceedings of the 20th International Meshing Roundtable, Paris, 2011

For use in optimisation, the advantage of the above results is that more efficient structured meshing strategies can be applied to the thin-sheet and long-slender regions. Then, it is only necessary to apply state-of-the-art but computationally expensive unstructured tetrahedral meshing to the remaining complex 3D regions.

In the S2T3 example, the whole engine model from CADfix was imported into Abaqus CAE (DS Simulia) where these meshing strategies were automatically applied to generate the model also shown in Figure 22. Subsequent modal analyses verify that these more efficient semi-structured meshes achieve solutions with similar accuracy to those from a completely unstructured mesh, but with **more than 50% reduction in overall Degrees of Freedom.** This substantial reduction leads to **faster solutions** and means **more optimisation cycles** are possible.

Another novel result [**R33**] from UBELFAST is developing the concept of "Simulation Intent"[32] as a mechanism to capture (from the start of the design process) the high level modelling and idealisation decisions used to create fit-for-purpose simulation models for analysis. Using Simulation Intent, once a decomposition and meshing strategy has been identified, model generation can be automated. As seen in Figure 23, Siemens NX8 has been used to demonstrate this process with industrial partners, creating 1D, 2D or 3D idealised meshed models as part of the overall product integration process scenario in test case S3P1.

In conclusion, these CRESCENDO results demonstrate a process for automatically creating efficient semi-structured meshes on typically complex aerospace structures. This reduces the cost of running 3D Finite Element Analyses, allowing these methods to be used earlier in the design process, and consequently reduce the risk of rework in later design stages.

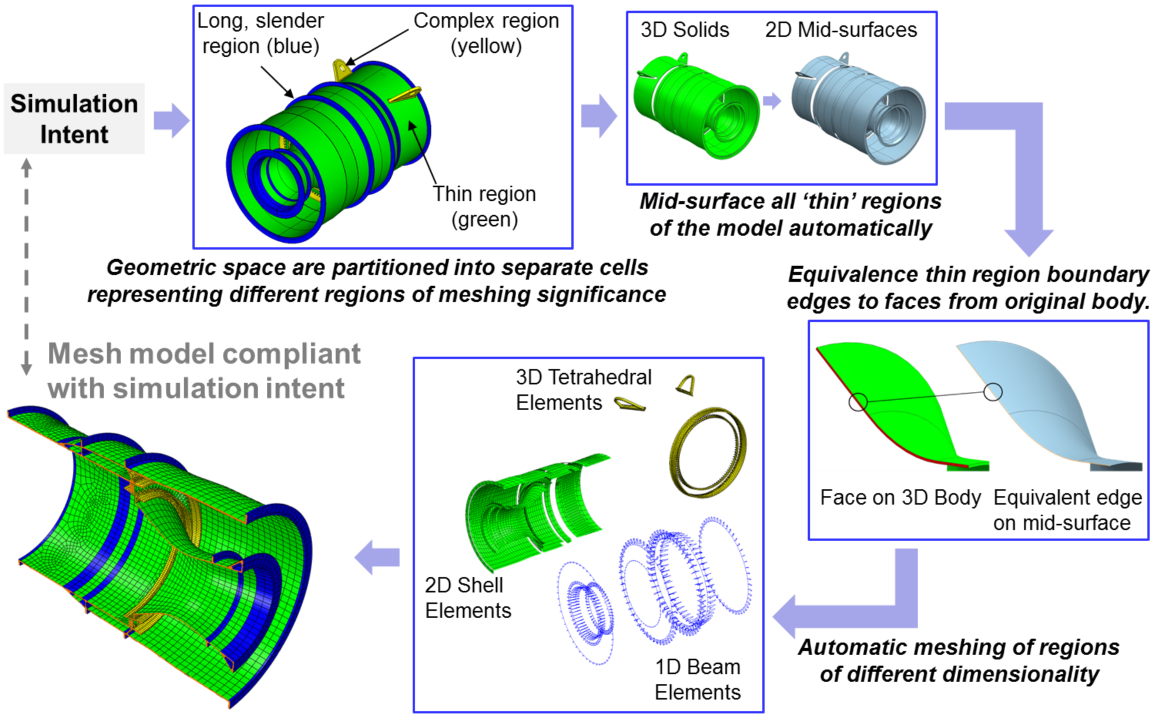

Figure 23: Simulation Intent used for automatic & fit-for-purpose meshing of an aero-engine intercase component

3.3.2 Advances in Multi-physics coupling processes and methods

A significant effort in several of the CRESCENDO thermal or power plant test cases delivered the CRESCENDO results related to improving multi-physics coupling processes and methods. Some examples are presented below.

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[32] "Automating analysis modelling through the use of simulation intent", by D. Nolan (UBELFAST) et al, accepted for NAFEMS World Congress, Salzburg, 2013

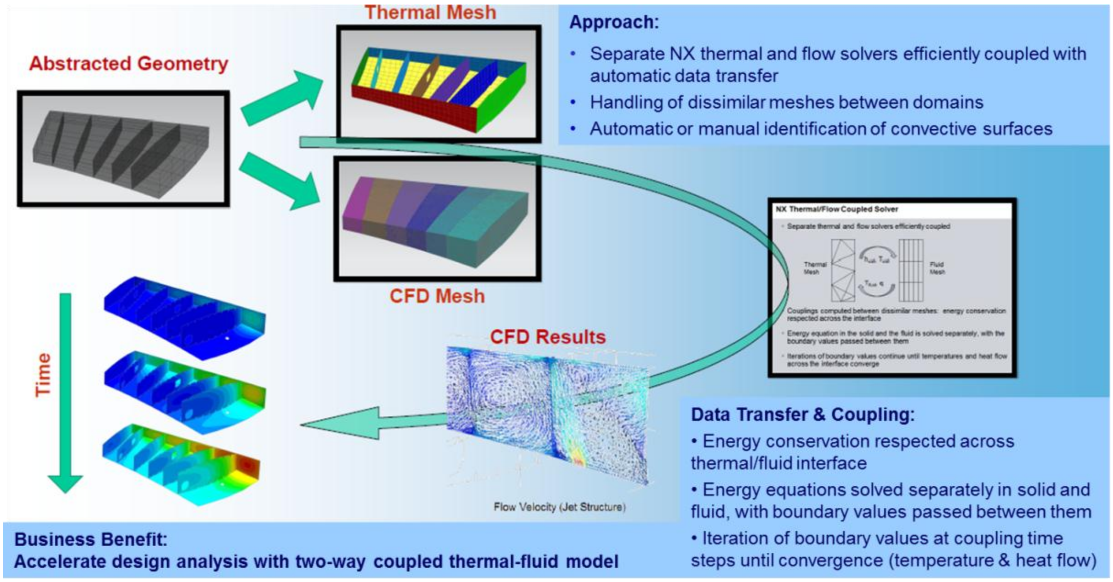
Efficient fluid-structure thermal coupling methods

In the last two decades, Computational Fluid Dynamics (CFD) methods have been heavily used for both external (e.g. aerodynamic) and internal (e.g. air and fuel systems) behaviour analysis in the aerospace industry. CFD and FE coupling approaches establish transfer of thermal information between the fluid and structure domains.

In the context of the thermal analysis of confined compartments test case S3T1, AI-UK have worked, with support from Airbus Engineering Centre India and SIEMENS, to improve both accuracy and time required for Fluid-Structure thermal coupling applied to typical aircraft whole wing fuel system studies [**R17, R64**].

Two approaches have been studied and the results are summarised as follows.

- Coupling processes using Siemens NX Thermal & Flow, as shown in Figure 24.
- Coupling processes using Ansys Mechanical & Fluent, as shown in Figure 25.



Approach:

- Separate NX thermal and flow solvers efficiently coupled with automatic data transfer
- Handling of dissimilar meshes between domains
- Automatic or manual identification of convective surfaces

NX Thermal/Flow Coupled Solver

- Separate thermal and flow solvers efficiently coupled

Couplings computed between dissimilar meshes: energy conservation respected across the interface

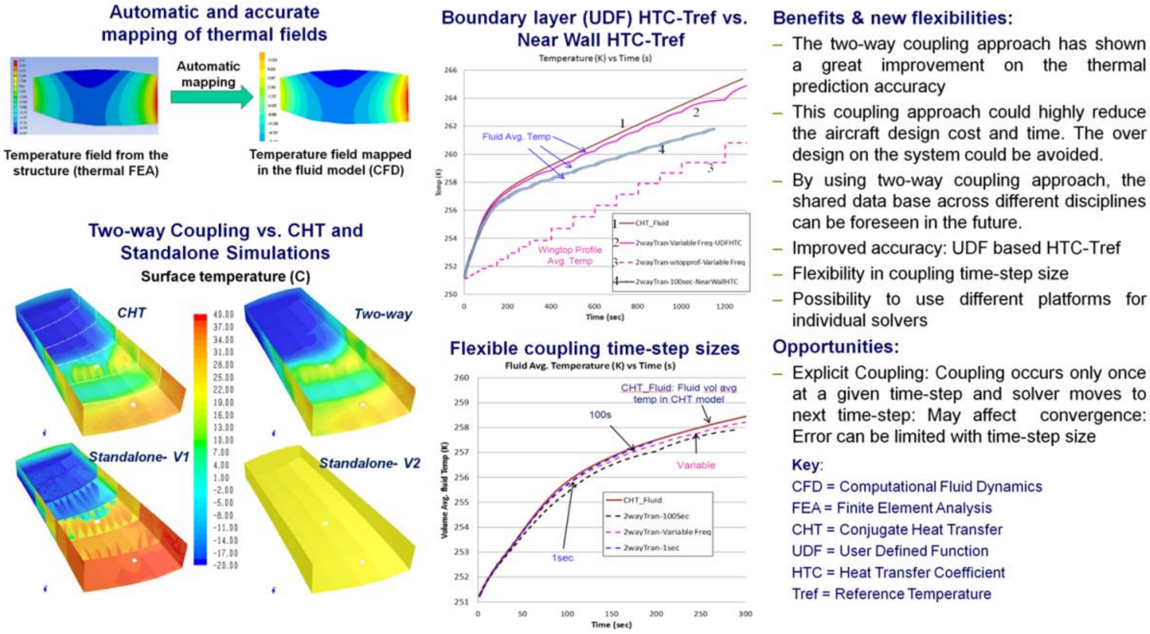
- Energy equation in the solid and the fluid is solved separately, with the boundary values passed between them
- Iterations of boundary values continue until temperatures and heat flow across the interface converge

Data Transfer & Coupling:

- Energy conservation respected across thermal/fluid interface
- Energy equations solved separately in solid and fluid, with boundary values passed between them
- Iteration of boundary values at coupling time steps until convergence (temperature & heat flow)

Business Benefit:
Accelerate design analysis with two-way coupled thermal-fluid model

Figure 24: Automated two-way transient coupling for thermal-fluid simulation of fuel tanks - using Siemens NX Thermal/Flow


Automatic and accurate mapping of thermal fields

Two-way Coupling vs. CHT and Standalone Simulations

Boundary layer (UDF) HTC-Tref vs. Near Wall HTC-Tref

Flexible coupling time-step sizes

Benefits & new flexibilities:

- The two-way coupling approach has shown a great improvement on the thermal prediction accuracy
- This coupling approach could highly reduce the aircraft design cost and time. The over design on the system could be avoided.
- By using two-way coupling approach, the shared data base across different disciplines can be foreseen in the future.
- Improved accuracy: UDF based HTC-Tref
- Flexibility in coupling time-step size
- Possibility to use different platforms for individual solvers

Opportunities:

- Explicit Coupling: Coupling occurs only once at a given time-step and solver moves to next time-step: May affect convergence: Error can be limited with time-step size

Key:
CFD = Computational Fluid Dynamics
FEA = Finite Element Analysis
CHT = Conjugate Heat Transfer
UDF = User Defined Function
HTC = Heat Transfer Coefficient
Tref = Reference Temperature

Figure 25: Automated two-way transient coupling for thermal-fluid simulation of fuel tanks - using Ansys Mechanical and Fluent

In summary, the main conclusions are as follows:

- A thermal mapping tool developed with Ansys Fluent has been tested and accurate interpolation has been obtained.
- Full automatic one-way and two-way coupling processes have been developed and tested with different solvers: Ansys Fluent and Mechanical, and Siemens NX Flow and Thermal (TMG);
- Both FE and CFD teams can obtain more realistic boundary conditions, reduce uncertainty and avoid over-design;
- The two-way coupling approach shows a great improvement on the thermal prediction accuracy; and could highly reduce aircraft design cost and time.

Multi-physics coupling for high fidelity modelling of aero-thermal behaviour in APU region

The design of air system exhausts is of crucial interest for AI-F in terms of overall aircraft performance. In order to prevent negative effects, the exhaust system must be designed to ensure that wall temperatures remain within prescribed limits; so that it does not induce a weight increase; and has only a limited effect on the overall drag.

Based on the GTA model (S2T1 test case), modelling approaches have been generated in the S2T2 test case to better predict aero-thermal behaviour in the APU region **[R45]**: one for the internal domain within the airplane; and one for the external domain outside the airplane to capture the thermal signature induced by the Jet-in-Cross-Flow (JICF), see Figure 26. The results **[R45]** are:

- Development of advanced CFD Models to accurately predict aero-thermal mixing between a hot jet (air system exhaust) and a transverse flow field (external flow), using: (a) RANS/LES[33] approach developed by CERFACS; and (b) Scale-Adaptive Simulation (SAS) approach developed by ONERA DMAE.
- Setting-up of a dual coupling process between three models: one thermal model + the two CFD models for a fully integrated multi-physics model.

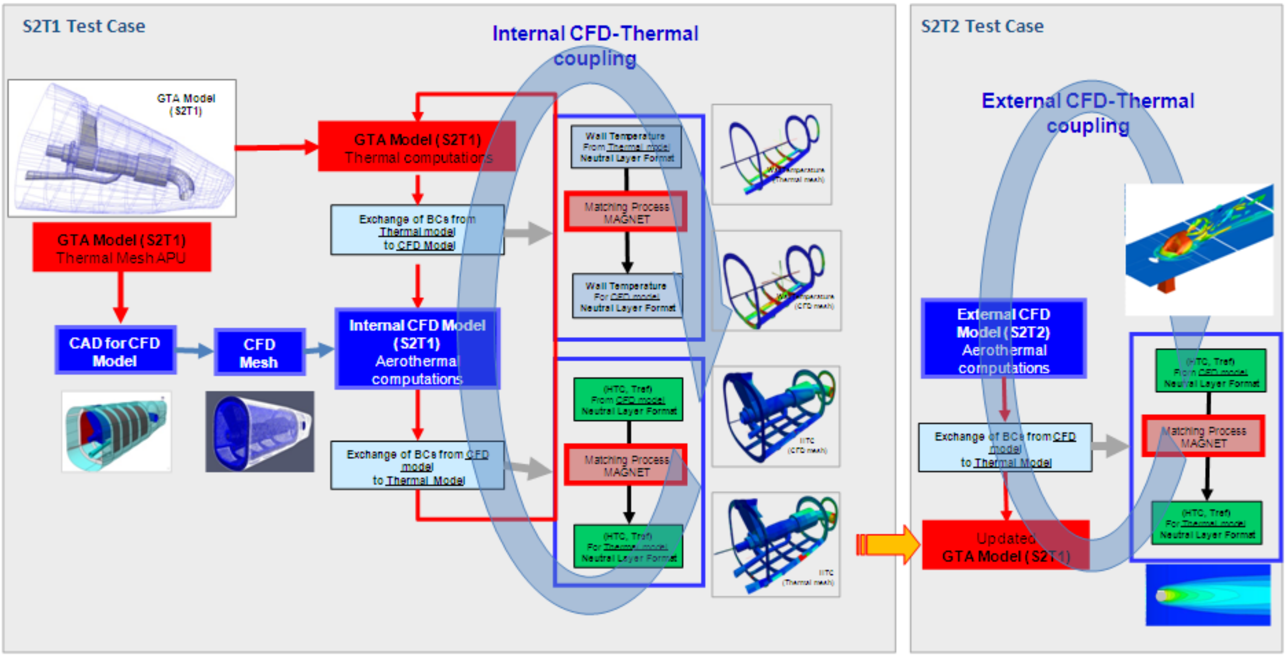


Figure 26: Multi-physics coupling (CFD-thermal) for aero-thermal prediction in APU region

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[33] RANS = Reynolds Averaged Navier Stokes method; LES = Large Eddy Simulation

Whole Aero-thermal Virtual Engine model (WAVE) and improved simulation of rain & hail ingestion

Improvements in the multi-physics coupling and mixed-fidelity modelling of rain and hail ingestion were made possible. The first development [**R30**] is a whole aero-thermal 3D multi-stage engine model (WAVE) and trajectory analysis within the engine using CEDRE (ONERA CFD code). The model is based on a SNECMA confidential engine architecture.

A related result [**R32**] concerns improving the simulation of rain & hail ingestion in engine performance calculations at the detailed design phase, using the PROOSIS tool developments by UNTUA:

- Development of physical models including: Particle trajectory model; Particle evaporation model; Droplet break-up model; Particle-surface interaction and water film model;
- Modelling water ingestion effects including: Scoop effect; Bouncing (fan cone); Fan effect – centrifugation; Evaporation (compressor, ducts); Variable bleed valve effect; Effect of water-to-air ratio on burner efficiency;
- Integration of rain/hail ingestion models in PROOSIS (UNTUA) through the development of appropriate engine component models (inlet, duct, compressor, fan, burner) with suitable interfaces (two-phase flow port);
- Creation of engine performance models (turbojet, turbofan) and simulation of rain ingestion.

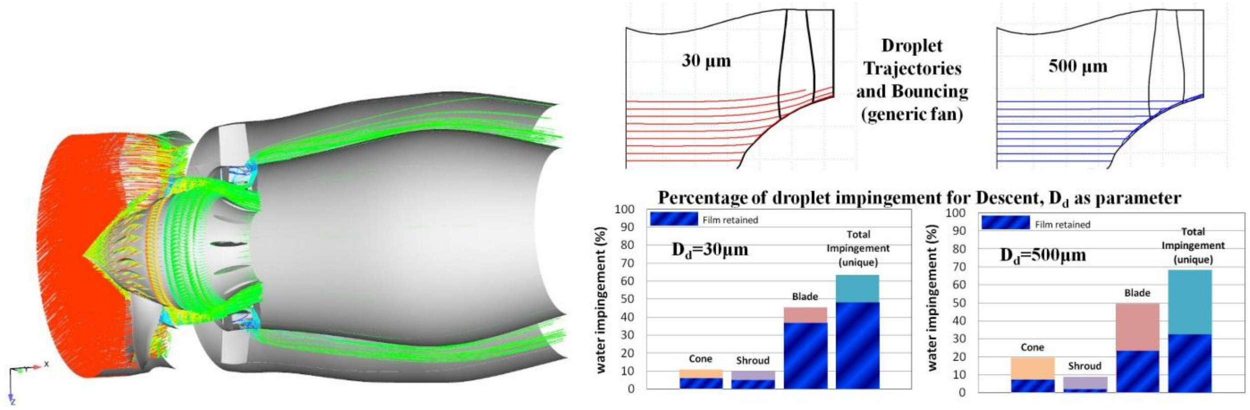

Figure 27: WAVE model and improved simulation of rain & hail ingestion

Advances in aero- and vibro- acoustic modelling and simulation

Noise prediction is a growing field of interest for aircraft & engine manufacturers. The installation effects (the difference between noise emitted by isolated and installed engines) are a key issue to achieve reliable predictions. The main contribution from CRESCENDO has been progress towards a fully numerical chain for better prediction during the design phase, rather than previous approaches mainly based on experimental work.

Two test cases have studied the coupling of state-of-the-art simulation methods to account for the physical phenomena at the scale of full aircraft configurations, and in different contexts. In both cases, the CFD, CAA (Computational Aero-Acoustics) and Vibro-acoustic tools mentioned are already used by Airbus & SNECMA, and all the results are directly applicable beyond CRESCENDO. Specific training sessions on these numerical aero-acoustics methods have taken place in Airbus, with ONERA and FFT as lecturers. Results are illustrated in Figure and have been reported[34] at scientific AIAA/CEAS aero-acoustic conferences.

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[34] For example "Computational AeroAcoustics of Counter Rotating Open Rotor Model on rear full scale airplane in cruise condition", by T. Le Garrec (ONERA) et al, in Proceedings of the 18th AIAA/CEAS Aeroacoustics Conference, Colorado Springs, USA, 2012

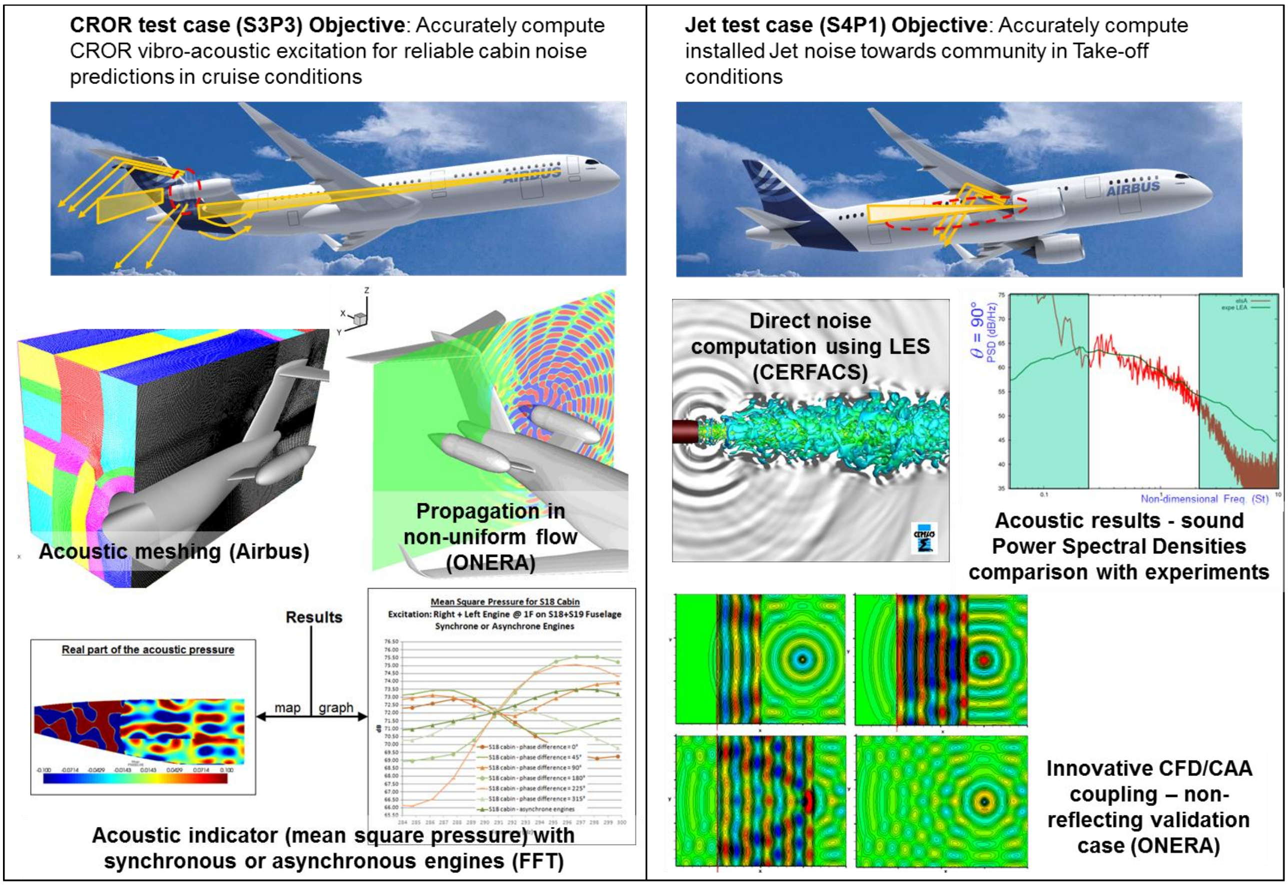

Figure 28: Advances in aero-vibro-acoustic modelling and simulation for CROR and Jet Noise

The **Aero-vibro-acoustic methods for Counter Rotating Open Rotor** (CROR) test case (S3P3), involving AI-F, SNECMA, ONERA, FFT (& MSC) studied CROR engines from a passenger perspective. Here, rotating parts emit noise that propagate across the boundary layer and lead to fuselage vibration, radiating noise perceived inside the cabin. The main results [**R81**] are:

- **"World's first" aero-vibro-acoustic full numerical chain** for CROR at full scale aircraft, with load cases investigation.
- Improvement of acoustic meshing strategies (refinement and smoothing) for a highly complex aircraft configuration; and full-scale application of these meshes.

In addition, a main focus for FFT has been to make the Actran vibro-acoustic simulation software act as a BDA client. This has been achieved by developing a python-based API supporting all features from pre- to post-processing, analysis templates, execution reports and XML Log files.

The **Aero-acoustic methods for installed Jet-Noise** test case (S4P1), involving AI-F, SNECMA, CERFACS and ONERA, studied conventional turbofan engines from a community noise perspective. Here, the jet noise sources are very wide spread, involving complex phenomena, reflected under the wing and refracted by the shear layer of the jet. Main results [**R80**] are:

- Improvements of ElsA software bringing progress on highly accurate unsteady CFD of the jet, using Large Eddy Simulation (LES). Good agreement with experimental data. Acoustic post-treatment done successfully.
- Development of strategies for accurate CFD/CAA coupling, with impressive progress in coupling LES with perturbed Euler equation solver (software sAbrinA v0). This is to be validated with analytic cases before application to full scale problems.

In conclusion, these advances promise a better understanding & confidence on noise predictions earlier in the lifecycle, contributing to passenger comfort of future aircraft whether conventional turbofan or CROR configurations; with reduced development cost due to 'virtual testing' on configurations not yet existing, and hence fewer experimental and flight test campaigns.

Multi-physics analysis of whole engine model with piezoelectric damping for rotor bearing

A workflow was developed by DLR[35] together with GKNAES & SNECMA [**R5**, see Figure 29], to assemble multi-level FE-models from different suppliers and then perform a multidisciplinary optimisation of piezo-electric actuator positioning and voltage. The optimization process includes a harmonic response analysis of the system. By evaluating the displacement and reaction force amplitudes, the optimal position and voltage of the applied piezoelectric actuators can be identified.

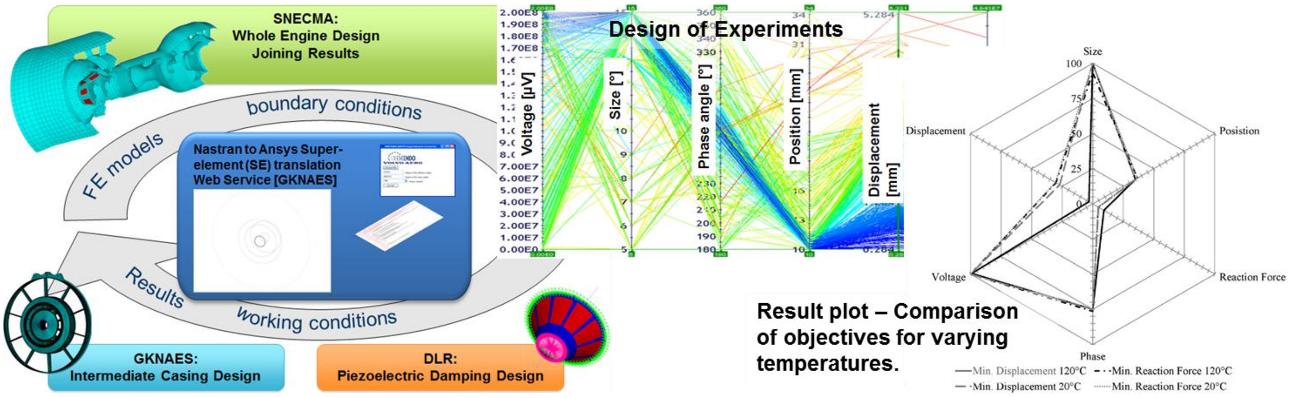

Figure 29: Multi-physics analysis & piezoelectric damping for engine rotor bearing

Coupled CFD High Pressure Turbine (HPT)-Low Pressure Turbine (LPT) simulation

For the turbine design optimisation stage in CREDO (S3P4 test case, see 3.6.3), several coupling scenarios are possible between the two major modules (HPT from RR-D and LPT from MTU): coupling with flexible interface average pressure; coupling with flexible interface radial pressure distribution; overlapping interface geometry and radial pressure. A sensitivity study of the interface definition [**R22**] quantified the level of expectation with regards to the overall efficiency improvement for the turbine.

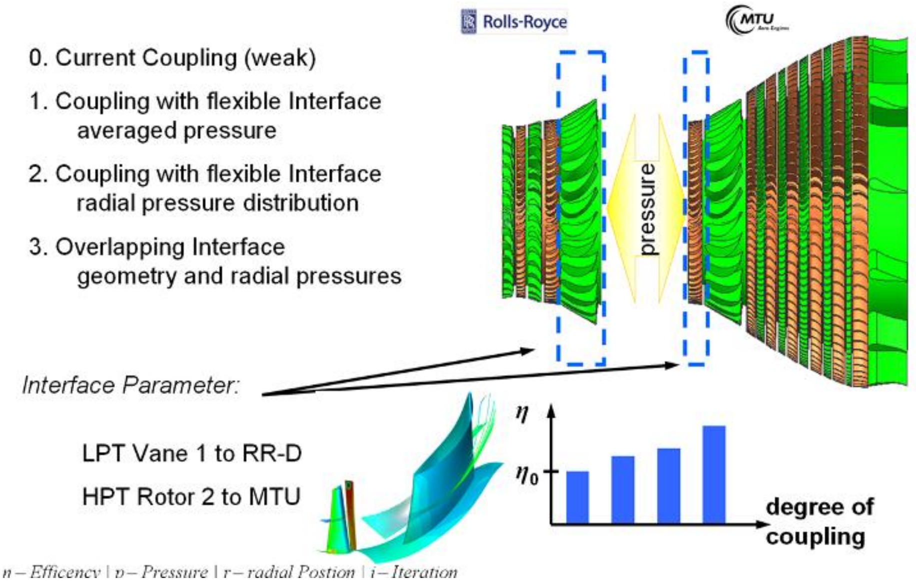

Figure 30: Coupled HPT-LPT simulation for engine design optimisation

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[35] "Simulation based method for integrating piezoelectric vibration control within overall engine design process", by F. Heinecke (DLR), accepted for NAFEMS World Congress, Salzburg, 2013

3.3.3 Surrogate Modelling Methods & Optimisation Strategies

For aircraft-level optimisation during the preliminary design phase, there is a need for efficient and computationally "cheap" simulations of aircraft system behaviour. For cross-partner collaboration, there is a need to share information between organisations to permit trade-off studies, but without compromising intellectual property. To enable such collaborations, a number of novel techniques were developed based upon the creation of surrogate models, also known as Response Surface Models (RSM). However, creating a surrogate model is not always straight-forward and needs intelligent tools as a support. In CRESCENDO, two such tools were used extensively, as shown in Figure 31:

- The MACROS set of Generic Tools for Approximation (GTApprox), developed by IRIAS. Application in CRESCENDO has led to enhancement of the toolset [**2**]. One such application [**R14**] was for the collaborative robust engine design optimisation test case S3P4, in order to support a stable data transfer between the industrial partners process for the coupled turbines. Another example with ECPTR, was to provide an approximation of a helicopter engine temperature profile (ref test case S3P2). One more example is the simulation of an aircraft cabin model with AI-D, ref test case S4E1, where a full-scale simulation of the cabin is replaced by a very fast surrogate model.
- The MultiFit integrated tool providing multiple fit methods, developed by NLR. A surrogate model was created by NLR[36] using the MultiFit tool [**R24**], for the "Collaborative approach to manage maturity indicator for design convergence between Airframe- & Engine-Manufacturer" scenario (also see 3.6.1). This was based on a dataset created from an automated knowledge-based preliminary engine design process at RR-D. This engine surrogate model could then be integrated as a black-box within the aircraft-level preliminary design optimisation tool SimCAD at AI-F. Another application using MultiFit was for Nacelle structural optimisation of a composite nacelle fan cowl door, with SHORTS [**R108**].

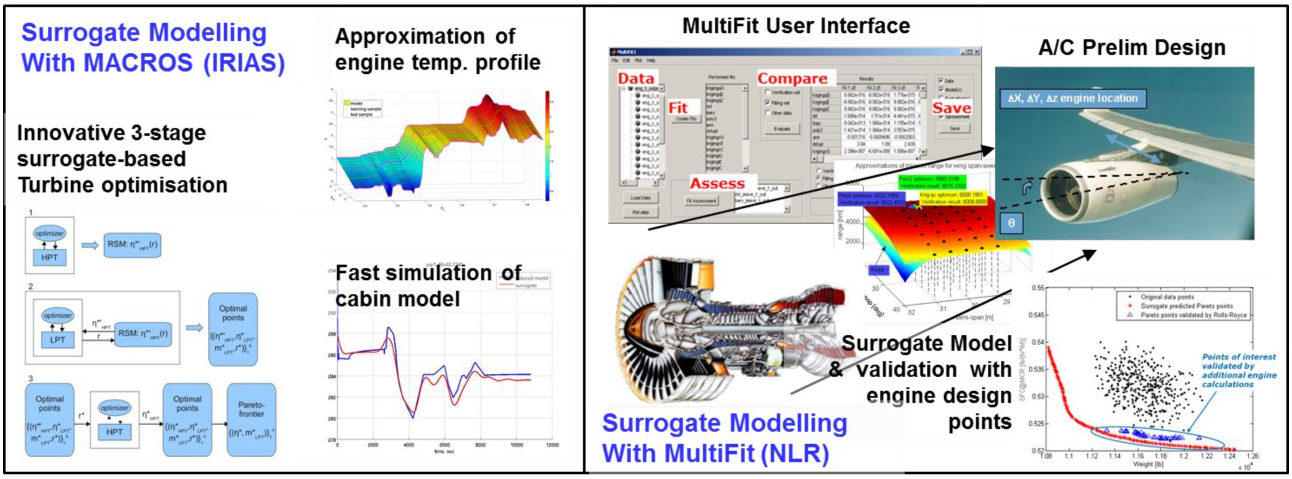

Figure 31: Surrogate Modelling Methods with (a) MACROS and (b) MultiFit

Given the expense of the whole engine thermo-mechanical simulations in test case S2T3, a surrogate modelling based optimisation approach was also employed [**R97**] by RR-UK together with USOTON and CIMNE. This approach attempts to represent the response of the objective function to changes in the magnitude of the design parameters based upon a small sampling of the design space. The sampling size directly influences the accuracy of the surrogate model and therefore the performance of the optimisation, however, increasing the number of sample points increases the number of simulations required and therefore the cost of the optimisation. Multi-fidelity surrogate modelling techniques offer an alternative by augmenting data from a

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[36] "Integrate Engine Manufacturer's Knowledge into the Preliminary Aircraft Sizing Process", by W. Lammen (NLR) et al, at AIRTEC "Supply on the Wings" conference, 2012

relatively small sample of high fidelity simulations with data from a large number of cheap simulations. Single and multi-fidelity surrogate models of engine performance were generated and hosted using web services and novel non-stationary surrogate modelling techniques were developed[37] to enable transient scalar and vector responses to be shared. The CRESCENDO results show a more accurate prediction of the objective function than the equivalent cost single fidelity surrogate, see Figure 32, and an improvement in the rate of convergence of the optimisation.

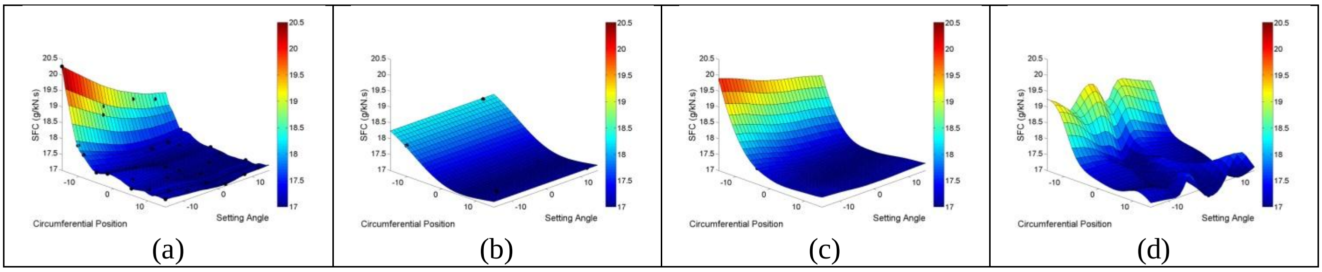

Figure 32: Comparison of surrogate modelling techniques
(a) the "true" response, (b) Kriging using 5 expensive simulations, (c) Co-Kriging and (d) an artificial neural network both using 4 expensive and 24 cheap simulations

ONERA, working in the test case S2P1 with RR-UK, demonstrated a bi-objective design and optimization[38], including two antagonistic objectives: weight minimization of both pylon-engine-nacelle installation and specific fuel consumption (SFC), while including Fan Blade Out event simulation at the same time [**R11**]. The process required the use of surrogate models for SFC and weight, and claims several innovations:

- Take into account engine flexibility to achieve weight saving and get a more realistic and more mature design (first time ever);
- Seek the trade-off between weight and SFC taking into account the internal loads redistribution (first time ever);
- Demonstrate and use external simulation capabilities while keeping proprietary data and models confidential through the use of surrogate models and web services from USOTON [**R12, R13**].

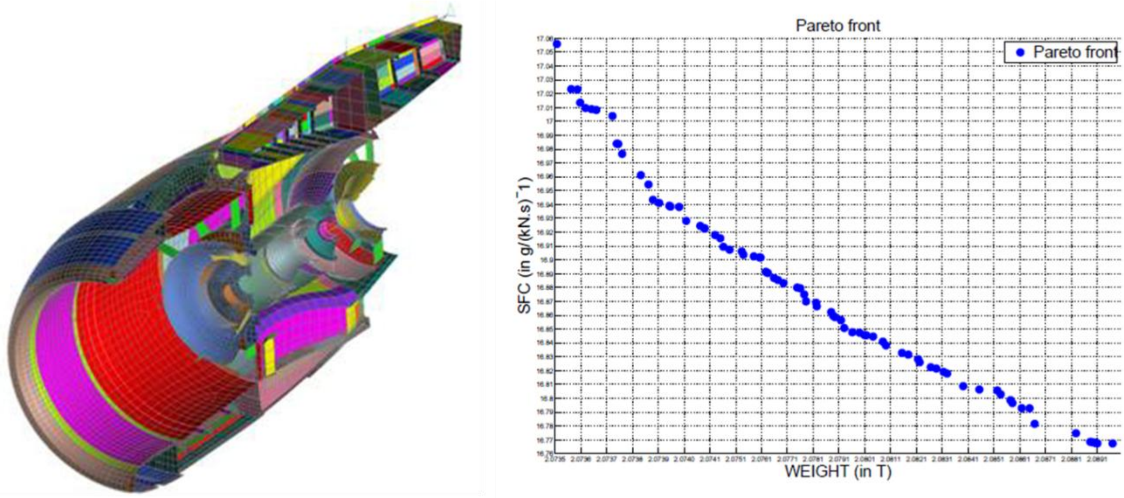

Figure 33: Pylon-Engine-Nacelle Assembly and
Final Pareto front obtained with 80 scalar optimizations with MSC Nastran SOL200

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[37] E.g. "Non-stationary kriging for design optimization", D.J.J. Toal & A.J. Keane (USOTON), Journal of Engineering Optimisation, 2012; or "Performance of an Ensemble of Ordinary, Universal, Non-Stationary and Limit Kriging Predictors", D.J.J. Toal & A.J. Keane (USOTON), Journal of Structural and Multidisciplinary Optimization.

[38] "Bi-objective optimization of pylon-engine-nacelle assembly: weight vs. tip clearance criterion", by D. Bettebghor & C. Blondeau·(ONERA) with D. Toal & H. Eres (USOTON); Journal of Structural and Multidisciplinary Optimization (SMO), 2012

In the same test case scenario, SAMTECH has demonstrated an Innovative Design with Bi-level Topology Optimisation[39] for a pylon design with AI-F. This result [**R79**] uses a bi-level optimisation scheme in the preliminary design stage to solve a structural design problem where both high-level variables (overall dimensions, position of attachments) and low-level variable (material densities) are processed in order to find a snapshot of the structural layout. For the high-level optimisation, an adaptive surrogate-based optimisation method (BOSS Quattro) with few variables is used to minimise the weight. At the lower-level, a gradient-based topology optimisation technique (SAMCEF TOPOL) with many variables is used. The developed strategy is demonstrated in the optimal design shown in Figure 34.

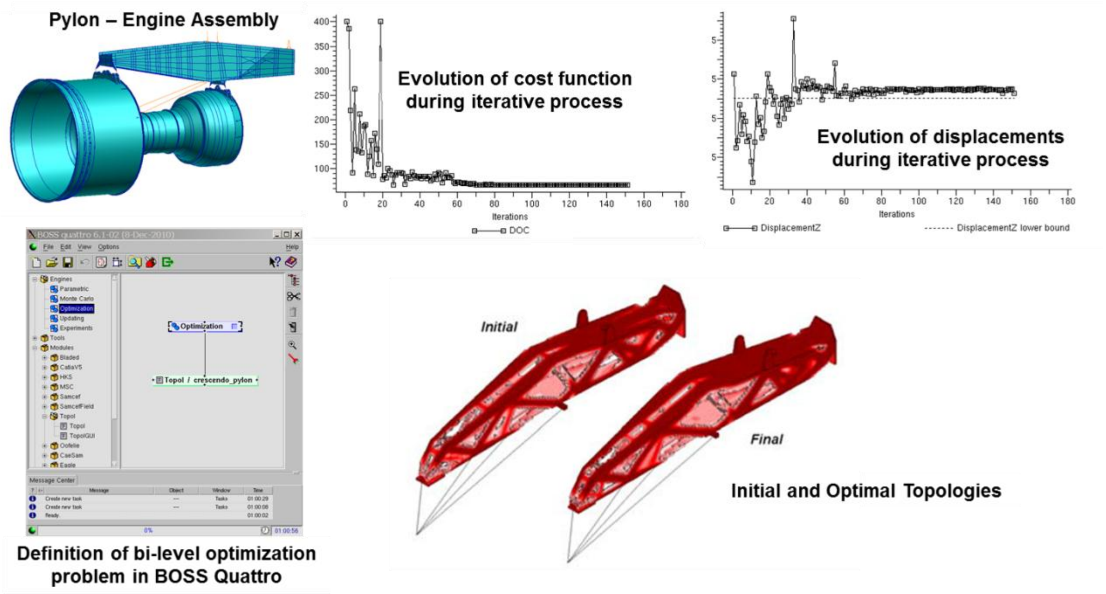

Figure 34: Bi-level parametric and topology optimisation scheme

3.3.4 Robust Design Optimisation methods

The main difference between deterministic and Robust Design Optimisation (**RDO**) is the presence of uncertainty in the latter, as shown in Figure 35. This makes the calculation unfold into two components: mean and standard deviation of objectives and constraints, where the “F” stands for a function or treatment in the objective space. The result of uncertainty propagation is that the objective space (Pareto-fronts for multiple objectives) often will be depicted in terms of mean and standard deviation. Then, the constraint expression is formulated into a calculation of the probability to satisfy the constraint and solving the problem requires estimation of the output probability density function (histograms).

Four approaches were studied. Each partner has either implemented or developed an uncertainty technique and two of the partners have tackled the problem of estimating the probability of constraint satisfaction or chance constraint (also known also as Reliability index). There has been a strong emphasis on collaborative aspects due to the multidisciplinary nature of the problem.

Uncertainty can be associated with the design variables (inputs to the model), as shown in the results from IRIAS and RR-D, where the application focus in CRESCENDO was on RDO of the engine (see CREDO within the Robust Detailed Design PPI test case S3P4, chapter 3.6.3).

- IRIAS developed an effective robust optimisation methodology [**R3**] with innovative algorithms in the **MACROS Generic Tool for Optimisation** (GTOpt), applied to the coupled high- and low-pressure turbine optimisation problem in S3P4 test case with RR-D and MTU. The use of MACROS helps to significantly reduce the number of objective functions evaluations and thus the overall optimization time.

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[39] “Innovative Design with Bi-level Topology Optimisation”, by A. Remouchamps & M. Bruyneel (SAMTECH) with S. Grihon (AI-F), 70th Annual SAWE International Conference, Houston, USA, 2011

- RR-D developed a fast RDO method **[R21]**, comparing the **Sigma Point approach** with Monte Carlo methods. This was shown to work for the RDO of the core engine in test case S3P4.

Uncertainty can be also associated with the simulation model itself, as shown in the results from SAMTECH and UCRAN, where the application focus in CRESCENDO was on optimising the preliminary engine performance and airframe sizing (see PPI test case S2P1, chapter 3.6.1).

- SAMTECH developed a "**polynomial chaos expansion based trust region**" method **[R27]**. This is a specialised surrogate model and was implemented in BOSS Quattro and coupled with the proprietary Airbus SIMCAD tool to compute the performance.
- UCRAN have developed[40] an **interactive** robust multi-objective optimisation **[R4]** implemented with their **AirCADia** software. The benefits for the user are to be able to obtain more information when it is most needed (early in the decision making process); to explore and interpret that information; and to integrate across the design lifecycle and extended enterprise.

	Deterministic (Classical)	**Robust Design Optimisation presence of uncertainty, ξ**	**Method to treat objectives in RDO, *F***	
Minimize Objectives	$\begin{cases} f_1(x) \\ \vdots \\ f_n(x) \end{cases}$	$\begin{cases} F[f_1(x,\xi)] \\ \vdots \\ F[f_n(x,\xi)] \end{cases}$	**IRIAS**	Trade-off mean objective and variance (standard dev)
			RR-D	Trade-off mean objective and variance (standard dev)
Subject to Constraints	$\begin{cases} g_1(x) \le 0 \\ \vdots \\ g_i(x) \le 0 \end{cases}$	$\begin{cases} \Pr\{g_1(x,\xi) \le 0\} \le Po_1 \\ \vdots \\ \Pr\{g_i(x,\xi) \le 0\} \le Po_i \end{cases}$	**SAMTECH**	mean objective
			UCRAN	mean objective +/- *k*·(standard deviation)

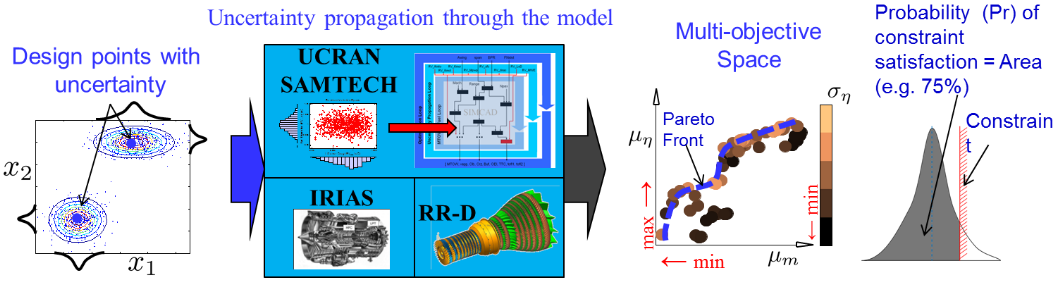

Figure 35: Deterministic versus Robust Design Optimisation

Several partners have expressed interest in exploiting the developed numerical methods for the modelling and propagation of uncertainty **[R86]**:

1. Modelling of Uncertainty Affecting Simulation Models: In addition to the possibility of modelling the uncertainty associated with the inputs of simulation studies, the designer is enabled to model also the uncertainty affecting simulation models. This is achieved through the numerical perturbation introduced on specific design parameters by random variables (RVs) with given statistical properties. Such random variables can be formulated via symmetric and non-symmetric PDFs (e.g. Gaussian, Triangular), depending on the noise and/or epistemic uncertainty associated with the models computing the design parameters to be perturbed.

2. Efficient Propagation of Uncertainty: Robust design studies can be efficiently performed by reducing the computational efforts required to effectively propagate the uncertainty affecting the inputs and/or the models of simulation workflows. **Univariate Reduced Quadrature** (URQ) has been developed by UCRAN as a novel method for fast uncertainty propagation, applied to compute an estimation of the statistical properties (mean and variance) of simulation outputs.

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[40] "Comparing Design Margins in Robust and Deterministic Design Optimisation", by M.D. Guenov, M. Nunez & A.D. Gondhalekar (UCRAN), in EUROGEN - Evolutionary and Deterministic Methods for Design, Optimisation and Control with Applications to Industrial and Societal Problems, Capua, Italy, 2011

The method allows the designer to specify also a minimum probability of satisfaction of the constraints considered in robust optimisation studies.

These methods were advanced by UCRAN (see Figure 36) to conduct the robust optimisation studies required in the Preliminary Multidisciplinary Power Plant Design test case (S2P1, also see 3.6.1). Specific requirements were the ability to handle Gaussian and Triangular distributions, modelling the uncertainty associated with the computation of specific simulation models, and efficiently propagating the uncertainty in workflows to estimate the probabilistic behaviour of particular design parameters.

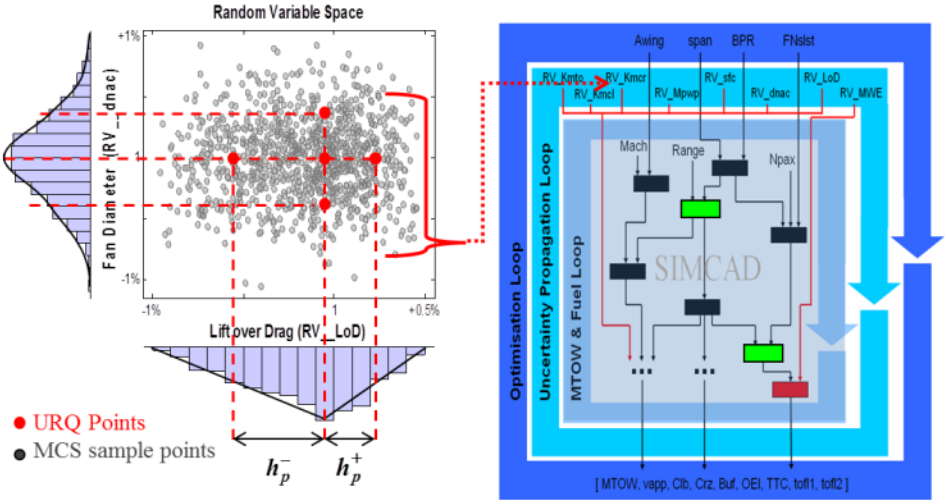

Figure 36: Uncertainty Propagation Method for Robust Optimisation studies

3.4 Value Generation Methodology and enabling Models & Tools

Ultimately, the success of an entirely new (or derivative) aircraft depends on how well it satisfies expectations. There are many stakeholders in the overall Air Transport System that express the "customer expectations" for an aircraft and its behaviour. Typical stakeholders include the Airlines, Airports, Airworthiness Authorities, and may also include passengers, flight / ground crew and maintenance organisations. The expectations of the aircraft manufacturers and supply chain are another important consideration. The product development task is complex and challenging, with a huge number of technologies need to be integrated and where many organisations need to work tightly together.

The main results from the Value Generation (VG) application case are now described, using collaboration capabilities and innovative engineering methods to demonstrate:

- How to ensure the capture and communication of this diversity of stakeholder and customer expectations;
- How to retain a focus on the value-adding contribution when establishing the technical requirements at all levels of the product design;
- How to make "value" a visible and tangible means to inform product development decisions such as the selection between alternative product concepts.

Further information can be found in the final deliverable[41] produced by the related CRESCENDO work-package team and in 19 or more papers & publications that have been produced during (and after) the project. One recent paper provides a complete overview[42] of the main Value-Driven Design methodology and its associated enabling models and tools.

3.4.1 Overall Value-Driven Design (VDD) methodology

The VDD methodology [**R48**] proposed by CRESCENDO will allow companies at multiple levels of the extended enterprise to start their early, conceptual work in a more relevant way i.e. based on context specific multi-dimensional value considerations. As shown in Figure 37, the VDD methodology relies on multiple collaborative iterations of a Value Creation Strategy (VCS, see below) at each concerned level, and with joint analysis phases between levels enabled by the BDA architecture specification. The CRESCENDO test case (S2V1) was limited to a two iteration process for VDD demonstration, summarised as follows:

1. Stakeholders expectations are captured and validated;
2. Needs are identified, analysed and rank-weighted;
3. First iteration of the Value Creation Strategy (VCS), including Value Drivers (VD's);
4. Quantified Objectives (QO's) identified on the basis of the rank-weighted needs;
5. Second iteration of the VCS, including refined VD's and QO's;
6. Value models are developed and used for the optimisation of early design concepts;
7. Requirements are established based on the rank-weighted QO's.

In these ways, the VDD methodology will complement Systems Engineering practice and enhance traditional Requirements Management processes with more mature & value-driven requirements.

Figure 37 also provides an example of how an aircraft level need can cascade through levels of the supply chain. In this example, the customer need "to be known for the passengers first" is translated at aircraft level in three main VDs, such as "cabin air quality", "cabin noise level", and "seat spacing". Of course, there could be additional value drivers such as "cabin lighting", "vibration level", or more detailed value drivers e.g. "leg room" or "texture of seat surfaces". The initial selection of the value drivers at aircraft level can be communicated in a first

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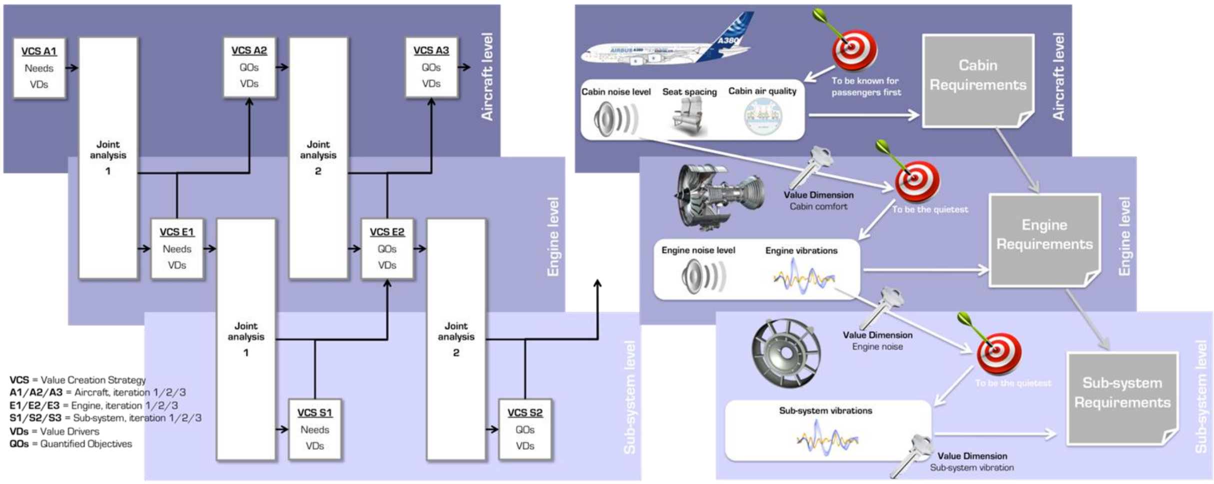
[41] "Validation of the system to link expectations to technical requirements", AI-UK et al, CRESCENDO Deliverable D2.2.4

[42] "Value-Driven Design - A methodology to Link Expectations to Technical Requirements in the Extended Enterprise", O. Isaksson (GKNAES) et al, accepted for 23rd Annual INCOSE International Symposium, Philadelphia, USA, 2013

iteration of the VCS to the engine level. The “cabin noise level” VD can be translated into more detailed drivers at engine level, such as “engine noise level” regarding air transmitted noise, and “engine vibrations” regarding structure transmitted noise. These may be further cascaded and characterized by the sub-system manufacturer, and so on.

Main partners involved in developing this result: AI-UK, EADS, GKNAES, with RR-UK, Pyramis, UINSAT, ULULEA, USOTON and Eurostep.



(a) VDD in the extended enterprise (b) Example of translating value drivers from one level to the next

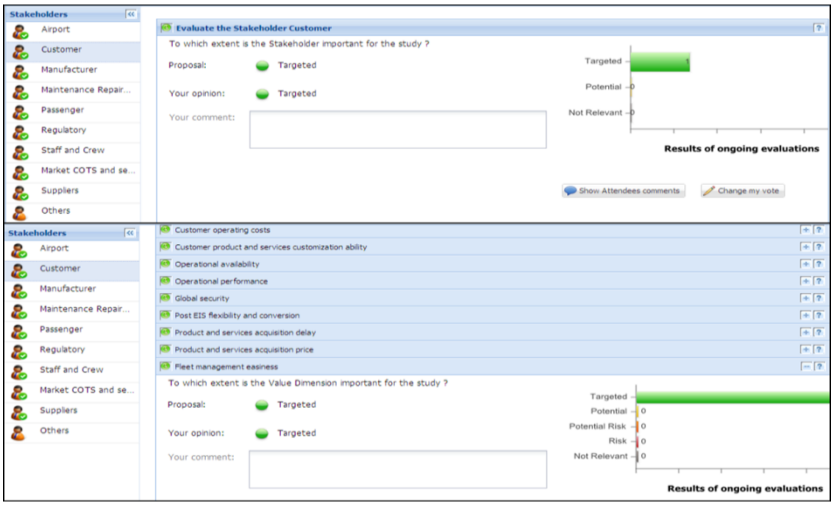
Figure 37: Value-Driven Design Methodology

3.4.2 Value Creation Strategy (VCS)

The VCS [R9] is the entity (or document) that describes the specific context for a VDD project. For each level of the enterprise, this includes: a set of rank-weighted Customer Needs (to be satisfied for identified stakeholders or customer profiles); a list of rank-weighted Quantified Objectives (with corresponding measurement criteria); and a set of Value Drivers (indicating key engineering characteristics given a specific VCS). To collaboratively elicit and rank the VDs, a survey process involving a panel of interviewees is used.

During CRESCENDO, tools to support the capture and sharing of the VCS data were also demonstrated. For example, a web application (SharePoint prototype shown in Figure 38) allows capturing and structuring of the stakeholder needs through a succession of votes regarding who are the key stakeholders, which of their value dimensions and VDs are judged most relevant. It was also shown how VCS data can be structured and shared using BDA web services; and transformed and managed in tools such as ISight or ENOVIA from DS.

Main partners involved in developing this result: AI-UK, EADS, DS.



Evaluate the Stakeholder Customer

To which extent is the Stakeholder important for the study ?

Proposal: ● Targeted

Your opinion: ● Targeted

Your comment:

To which extent is the Value Dimension important for the study ?

Proposal: ● Targeted

Your opinion: ● Targeted

Your comment:

Figure 38: Value Creation Strategy – voting tool

3.4.3 Value-oriented and visualisation models supporting Concept Down-selection

To demonstrate a VDD approach in the concept down-selection process for engine architectures, a conventional aero-engine configuration and a more electric engine are compared in terms of Surplus Value they generate during their operational life. In this scenario, RR-UK assessed the alternatives by using performance, cost (unit, maintenance, life-cycle, etc.), Surplus Value, and design merit or "goodness". The **Surplus Value Model** (SVM) **[R60]** provides an economic measure of profitability, using engine, aircraft and operational parameters as inputs, and calculating the surplus value generated by a fleet of aircraft for a given operational period. The two most important aspects are representations of customer revenue and operating costs, balancing product price with manufacturing cost. These models were implemented using Vanguard Studio[43], where existing models were extended to include engine maintenance cost. A schematic view is presented in Figure 39. Preliminary simulations for the two architectures resulted in a decrease in the whole engine unit and maintenance costs and thus an increase in the SV of an aircraft fleet using more electric aero-engine architectures.

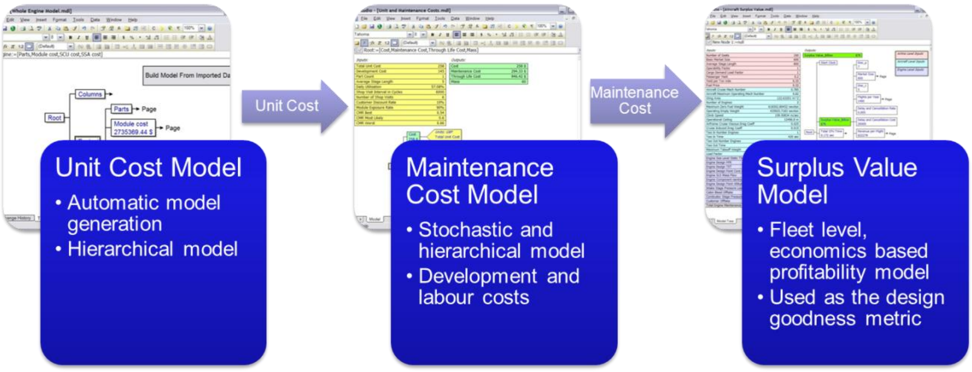
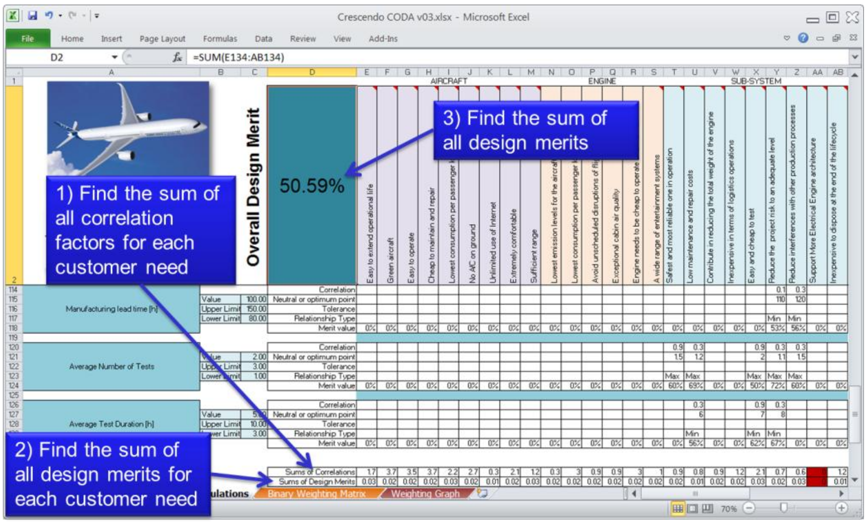


Figure 39: Schematic view of Unit Cost, Maintenance Cost, and Surplus Value models

In addition, to introduce VDD methods in preliminary design optimisation **[R7]**,within S2P1 test case, an interface between the SVM and SimCAD (an Airbus aircraft sizing code) was demonstrated [R61], using BDA Web Services and a "merging model" created dynamically (at run time) in the AirCADia software (UCRAN).

To calculate an overall "design merit" that represents the value contribution of conceptual alternatives to the desired VCS, an excel-based Customer Oriented Design Analysis (**CODA**) model was developed by USOTON[44], as shown in Figure 40 **[R8]**.



1) Find the sum of all correlation factors for each customer need

2) Find the sum of all design merits for each customer need

3) Find the sum of all design merits

Figure 40: Extract from overall Design Merit calculation using CODA

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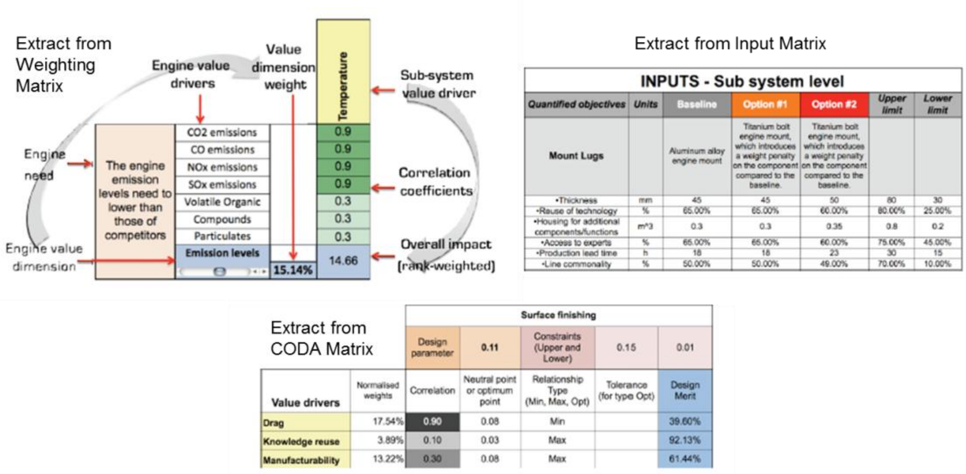
[43] See http://www.vanguardsw.com/

[44] "Mapping Customer Needs to Engineering Characteristics: An Aerospace Perspective for Conceptual Design", by M.H. Eres (USOTON) et al, accepted for Journal of Engineering Design, 2013

Alternatively, at sub-system or component technology level, **EVOKE** (Early Value Oriented design exploration with KnowledgE maturity)[45] **[R59]** performs a qualitative value assessment and also produces a design merit score. As shown in Figure 41, EVOKE employs 3 matrices: the *Weighting Matrix* (WM), which cascades down the system-level VCS to sub-system value drivers, the *Input Matrix* (IM) which gathers information about the characteristics of each design alternative being considered, and the *CODA* matrix, which renders the Design Merit score. These matrices are complemented by a method that provides a feedback to the designers about the reliability of the value analysis results, which is about the *Knowledge Maturity* on which the value models are built. Within CRESCENDO, EVOKE was demonstrated using a case study related to the development of an aero-engine Intermediate Compressor Case (IMC) as the reference design.



Extract from Input Matrix

INPUTS - Sub system level

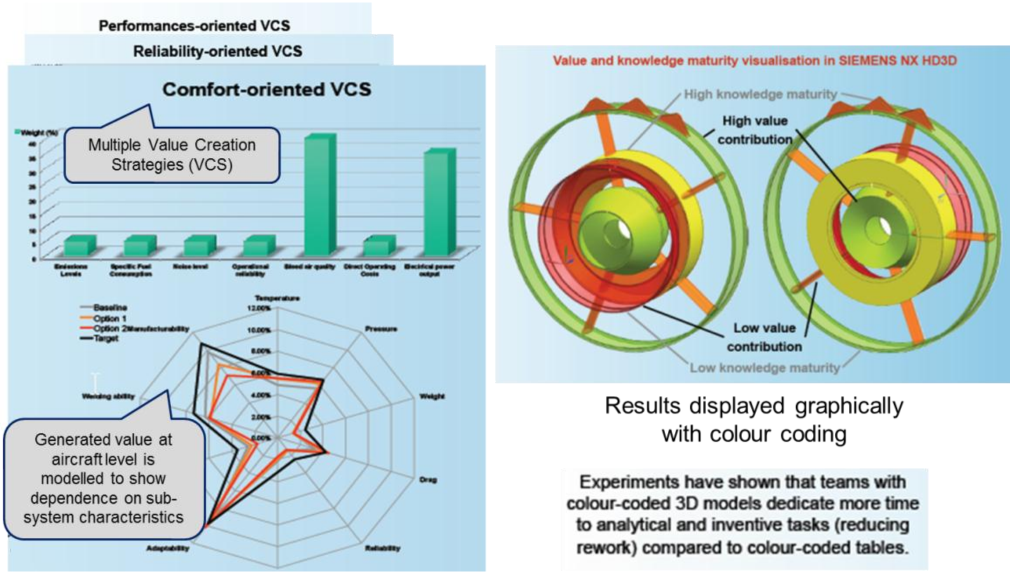
Quantified objectives	Units	Baseline	Option #1	Option #2	Upper limit	Lower limit
Mount Lugs		Aluminum alloy engine mount	Titanium bolt engine mount, which introduces a weight penalty on the component compared to the baseline.	Titanium bolt engine mount, which introduces a weight penalty on the component compared to the baseline.		
•Thickness	mm	45	45	50	80	30
•Reuse of technology	%	65.00%	65.00%	60.00%	80.00%	25.00%
•Housing for additional components/functions	m^3	0.3	0.3	0.35	0.8	0.2
•Access to experts	%	65.00%	65.00%	60.00%	75.00%	45.00%
•Production lead time	h	18	18	23	30	15
•Line commonality	%	50.00%	50.00%	49.00%	70.00%	10.00%

Extract from CODA Matrix

		Surface finishing				
		Design parameter	0.11	Constraints (Upper and Lower)	0.15	0.01
Value drivers	Normalised weights	Correlation	Neutral point or optimum point	Relationship Type (Min, Max, Opt)	Tolerance (for type Opt)	Design Merit
Drag	17.54%	0.90	0.08	Min		39.60%
Knowledge reuse	3.89%	0.10	0.03	Max		92.13%
Manufacturability	13.22%	0.30	0.08	Max		61.44%

Figure 41: The EVOKE process

Finally, to display the results of the EVOKE value assessment, and promote communication and collaboration within the design team, an approach to use **color-coded 3D CAD models [R18]** has been implemented. This uses Siemens NX 3DHD visual reporting[46] and was tested both in industry and in design sessions with students.



Results displayed graphically with colour coding

Experiments have shown that teams with colour-coded 3D models dedicate more time to analytical and inventive tasks (reducing rework) compared to colour-coded tables.

Figure 42: Colour-coded visualisation of IMC using Siemens NX HD3D visual reporting

Main partners involved in developing these results: RR-UK, USOTON, EADS, GKNAES, UCRAN, ULULEA, SIEMENS.

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[45] "Value-oriented concept selection in aero-engine sub-systems design: the EVOKE approach", by M. Bertoni (ULULEA) et al, accepted for 23rd Annual, INCOSE International Symposium, Philadelphia, USA, 2013

[46] "Using 3D CAD models for value visualization: an approach with SIEMENS NX HD3D Visual Reporting", by M. Bertoni (ULULEA) et al, accepted for publication in Computer-Aided Design and Applications Journal, 2013

3.5 Thermal Aircraft Behaviour Use Case

The Thermal Aircraft Behaviour Use Case was used to provide an overall integration focus to drive development of both BDA collaboration capabilities and engineering methods. Principally, this provides a joined up view from three of the CRESCENDO test cases i.e. S2T1, S3T2 and S4T1.

Examples of BDA engineering methods for Thermal analysis and design have been introduced in chapter 3.3. This section now reports how the BDA collaboration capabilities introduced in chapter 3.2 are exploited to enable two key architecture and integration processes:

- Global Thermal Aircraft (GTA) architecture process;
- Advanced equipment integration processes.

These two processes are introduced in Figure 43 below, and then further described in the next sections. The GTA architecture process (purple arrows) launches first and cascades technical requirements and specifications to component, system and equipment teams. Next the equipment integration process (cyan arrows) takes models provided by the suppliers and integrates these up to aircraft level, allowing confirmation that the configuration meets the targets specified by the architects.

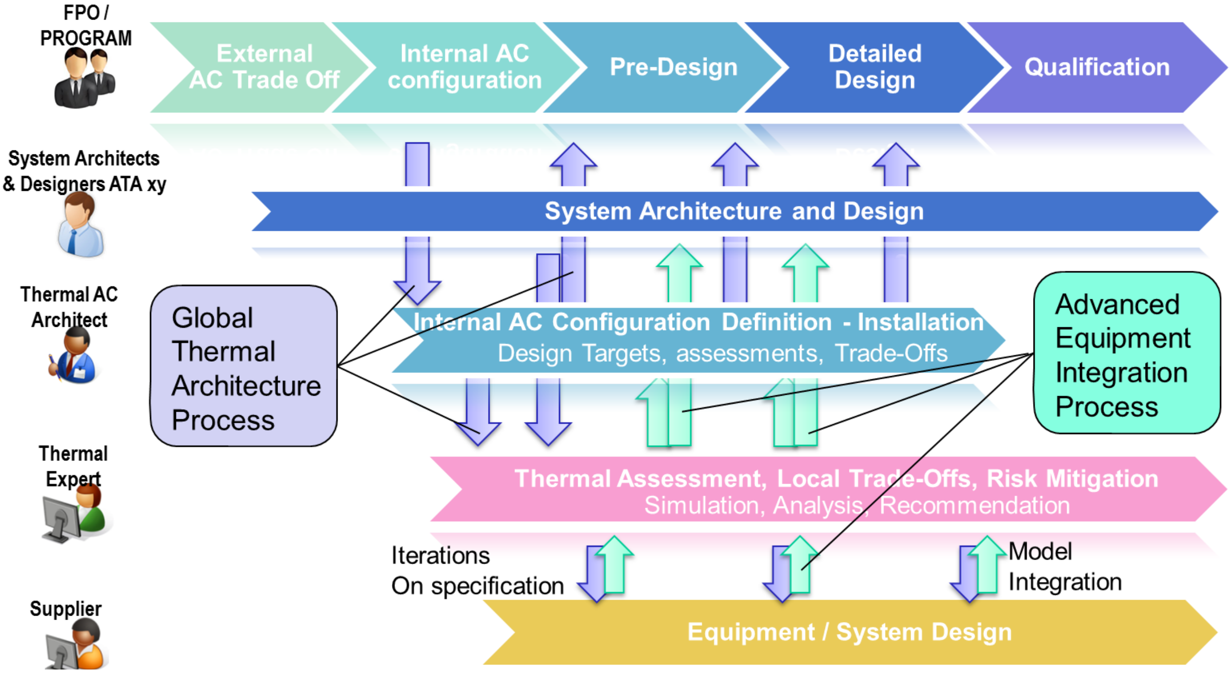

Figure 43: Global Thermal Aircraft Architecture & Equipment Integration processes

3.5.1 Global Thermal Aircraft (GTA) Architecture Process

The development of next generation aircraft faces an increasing thermal architecture challenge due to the incrementing number of heat sources; more dissipative equipment; and more sensitive and less conductive structures (in particular composite).

The GTA process addresses this challenge of “thermal architecture” to secure earlier integration of the thermal constraints in the architecture trade-off phase and the preliminary design at the overall aircraft level, continuously managed and supported by a monitoring of the design convergence to the thermal targets along the aircraft life cycle.

A key improvement comes from applying the BDA collaboration capabilities and BDA dataset concept for architecture, design and multidisciplinary analysis. This evolving dataset comprises models based on a large set of diverse data that include aircraft geometry, material definitions, weight, environmental parameters, mission scenario definitions, and system architecture descriptions. The thermal analysis process requires strong multidisciplinary contributions (engineering disciplines, equipment suppliers and risk sharing partners) where interface data and models are exchanged or integrated.

This capability was demonstrated by Airbus, Alenia, Thales, and IAI, with multiple inter-connected BDA platform installations supported by solutions from DS, LMS, Eurostep and MSC, enabling thermal actors across all four company sites to share information according to the BDA Business Object Model (BOM).

The process (Figure 44) starts with the Thermal architect specifying the initial configurations for analysis using the DS (ENOVIA, SIMULIA) and LMS (Imagine.Lab) platforms. Key information is published via the Eurostep Share-A-space platform and is retrieved by aircraft level thermal modelling experts at Airbus where Siemens NX/TMG is used to build and execute thermal simulations of the global thermal aircraft (GTA). Again, key information is published as part of the growing BDA dataset, to be accessed by IAI as Auxiliary Power Unit (APU) supplier, Alenia as cabin systems supplier and Thales as Avionics supplier. These suppliers use their internal IPR protected processes and tools to design, optimise and simulate the behaviour of their equipment, and then publish key thermal characteristics to the BDA dataset. Throughout this process, the shared distributed BDA dataset provides a basis for design review and decision making at every level of integration.

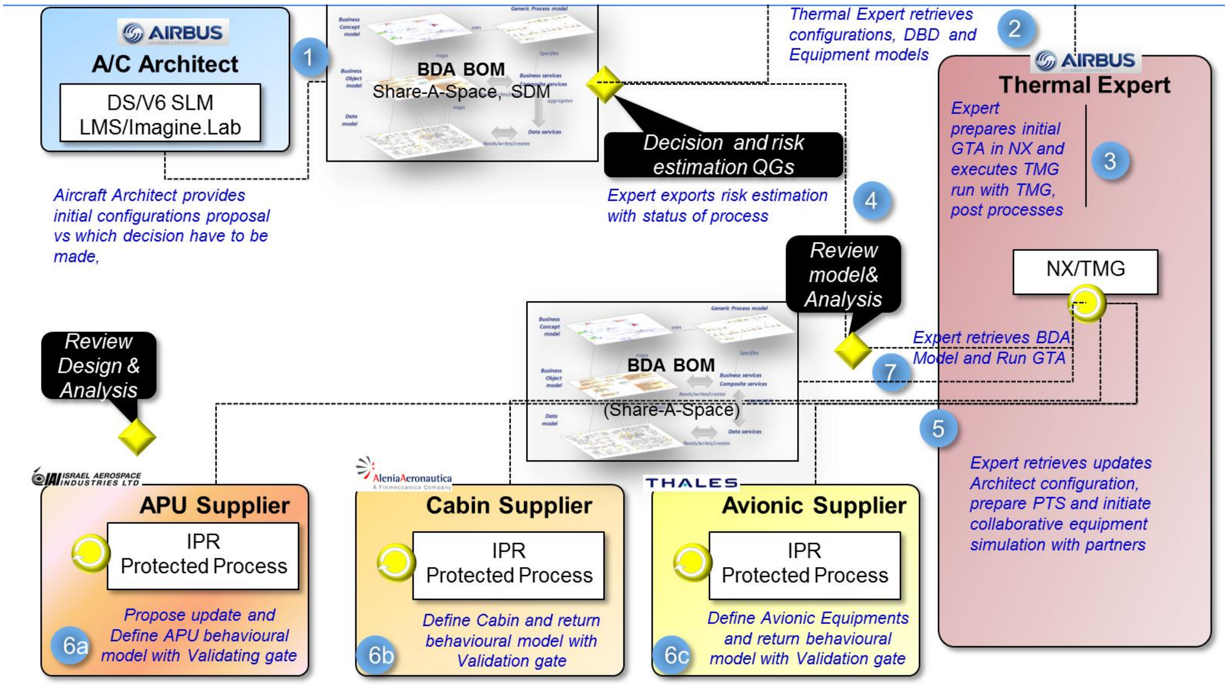

Figure 44: Developing the Thermal Aircraft along the lifecycle

The concept of an “Architect Cockpit” is a key innovation of CRESCENDO to support the role of Architects (see 3.2.3). In this use case, Thermal Architect Cockpit prototypes (Figure 45), demonstrated by both DS & MSC, configured multiple viewpoints for Architect interaction:

- Presenting thermal data from both OEM and suppliers, including requirements, systems & 3D block diagrams, thermal results, key characteristics, traceability, and timelines.
- Recording decisions and instructions from the Thermal Architect, and relaying these to the teams to drive next actions to mature the design.

Specifically, the following capabilities were demonstrated:

- Cascading the technical requirements to the teams involved in thermal assessments;
- Studying earlier new challenging design configurations, organizing and launching the trade-offs in conjunction with all the relevant disciplines;
- Analysing, ranking, and challenging the solutions with respect to thermal targets, with the support of experts through comparative studies and sensitivity analysis;
- Anticipating & solving the risks or penalties induced by Thermal behaviour on the global aircraft architecture;

- Collecting, analysing, and compiling the margins and their impacts on the global aircraft design;
- Managing traceability and accountability for the final thermal architecture and recording decisions for integration and installations;
- Ensuring that the final configuration is compliant with the performance targets specified by the Business.

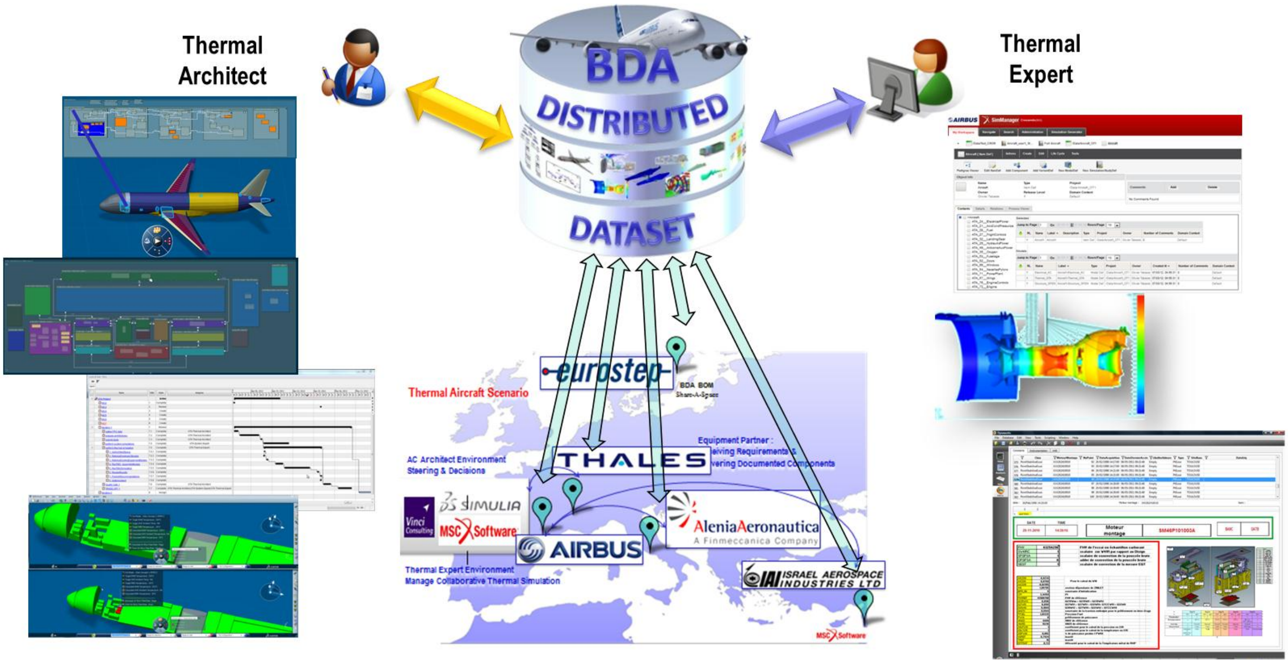

Figure 45: Thermal Cockpit integrates viewpoints to allow Architect to pilot the thermal design

3.5.2 Advanced Equipment Integration Process

Today, most disciplines and equipment suppliers work efficiently locally to achieve near optimal designs, therefore the most margin and opportunity for progress lies in better transverse integration of the systems and the equipment at overall aircraft level.

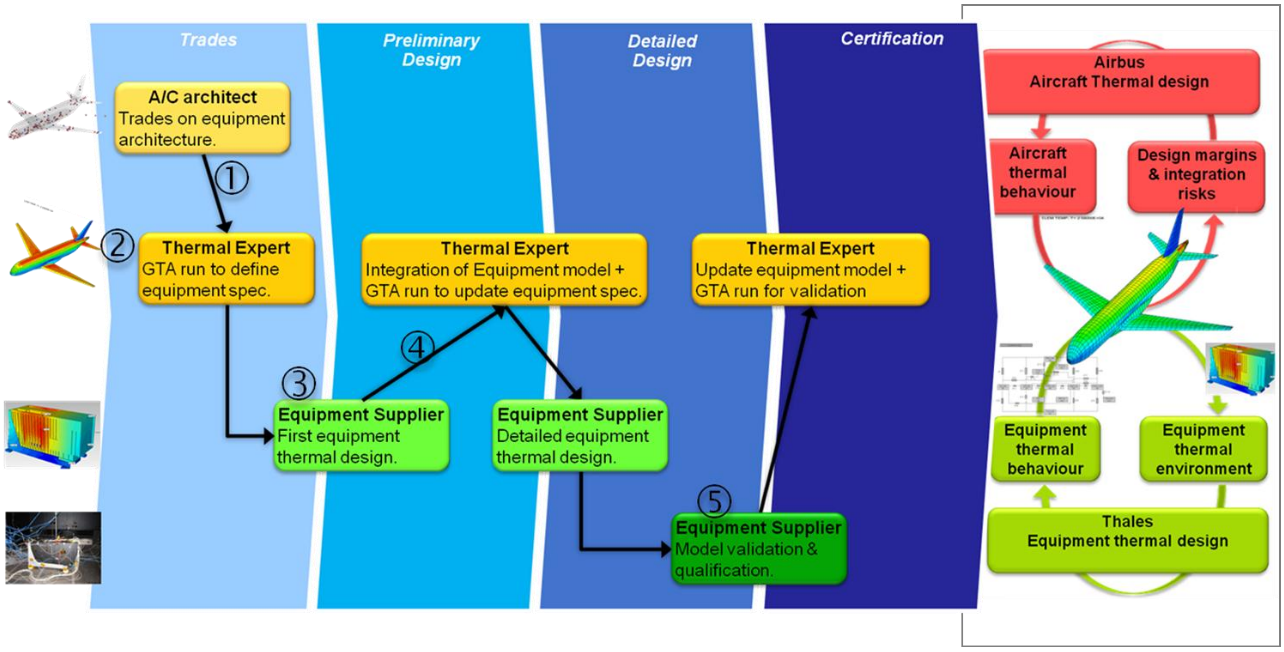

Figure 46: Integration of equipment thermal design into GTA

The Advanced Equipment Integration process [**R90**] focussed on driving capabilities to support the detailed collaborations between system integrators and suppliers (Figure 46). At the aircraft or system level, the thermal architect is managing thermal behaviours, risks and margins in the context of the overall aircraft and system design. At the equipment level, the supplier is managing the design and thermal behaviour of the equipment operating in the thermal environment of the overall aircraft or system.

At the aircraft level, one example of a detailed methods result from CRESCENDO is a genetic algorithm [**R91**] developed by ALTRAN to support finding the best design compromise regarding the location and distribution of equipment in the aircraft from a thermal point of view.

This advanced equipment integration process can be seen further in the context of the three supplier scenarios indicated in Figure 44 i.e. Avionics, Cabin Systems and APU compartment, supporting both aircraft level and zone level thermal integrated design.

For the avionics supplier scenario, a key advance from CRESCENDO is the development of Compact Modelling methods and the use of Equipment Neutral Thermal Models (ENTM). These compact models may be developed by each supplier to model how equipment performance and thermal behaviour varies according to operational scenario and thermal context. The architect or system integrator develops a thermal network model that integrates models of different equipment together with models of thermal environment behaviours, according to the overall aircraft or system architecture.

In the CRESCENDO test case (S3T2) example, the avionics equipment was provided by Thales. As shown in Figure 47, the internal Flotherm CFD model used at Thales was automatically reduced to create an ENTM (using Minitan) as an interface to the aircraft thermal architect. To achieve this model reduction, ULIM developed a novel and rapid procedure [**R25**] for generating compact thermal-fluid models (CTFM)[47] providing accurate results considering the computational saving, and protecting the IP of the equipment supplier.

These models were used to demonstrate an improvement in the equipment thermal design convergence plan and to optimise the equipment design with regards to the real thermal environment e.g. in terms of the sizing case and mean time between failure (MBTF).

In a final stage of the equipment integration process, a virtual testing approach has been used to validate the equipment reduced model by comparison with experiment test results, and de-risk the equipment qualification process (see 3.7.4).

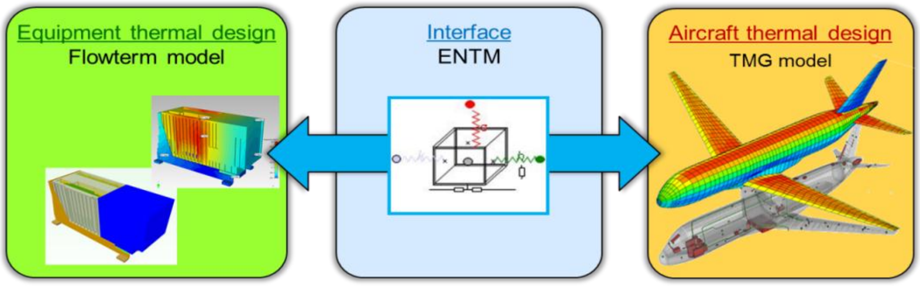

Figure 47: Equipment Neutral Thermal Models to make interface with suppliers

For the cabin systems scenario, ALENIA (together with USALENTO & UTORINO)[48] developed bi-level models for the preliminary design of aircraft cabin layout and optimisation of the cabin Environmental Control System (ECS) in a collaborative context [R75], as shown in Figure 48. From an engineering methods perspective, this demonstrated the detailed multidisciplinary optimisation of air system components and internal airflows for passenger comfort in the context of an overall optimised thermal design. From a collaboration point of view, MSC SimManager was used for the simulation process setup, and to demonstrate the exchange of model networks and management of a design change request, approval processes and quality review checks.

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[47] "Development of Compact Thermal-Fluid Models at the Electronic Equipment Level", by J. Stafford et al (ULIM), in Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE), Denver, Colorado, 2011

[48] "Multidisciplinary Design Optimization of Aircraft Cabin Environment", by A. Corallo & H. Barham (USALENTO) with P. Borelli & G. Mirra (ALENIA), at Movimento Italiano Modellazione e Simulazione (MIMOS), Rome, 2012

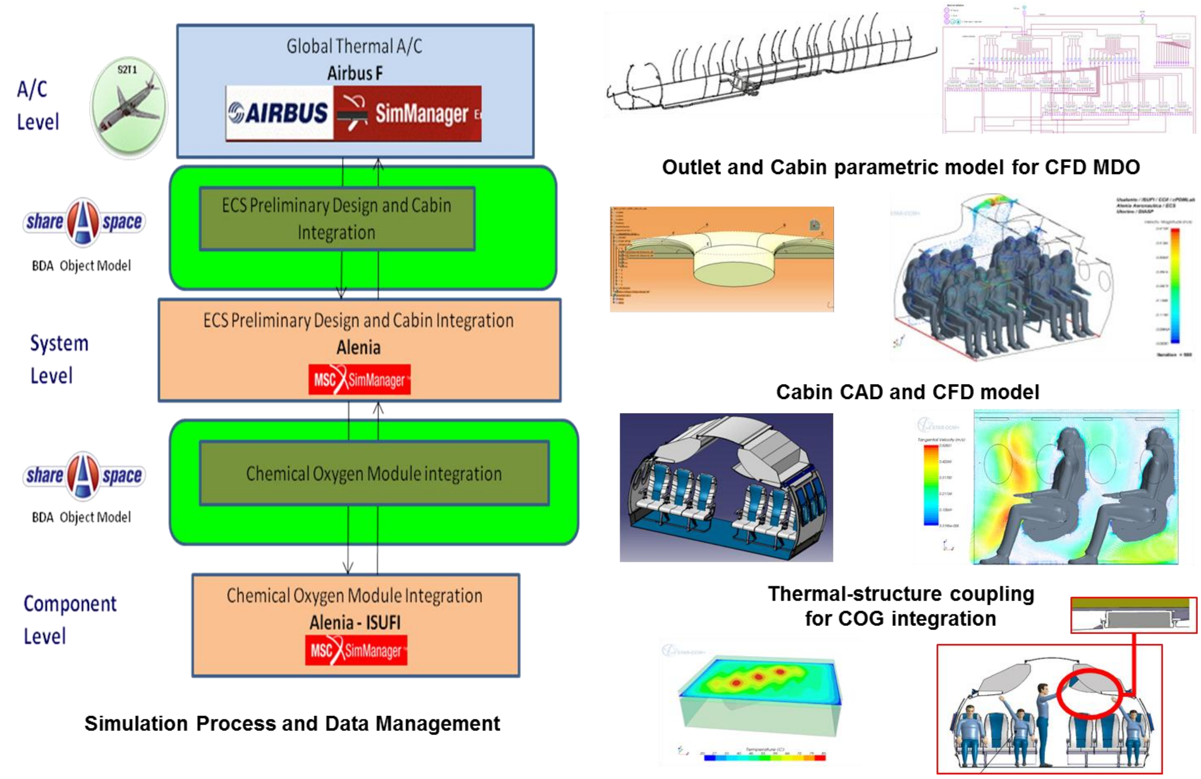

Figure 48: Cabin systems preliminary design integration and optimisation for passenger comfort

Finally, for the Auxiliary Power Unit (APU) compartment scenario, IAI developed a bi-level design optimisation process [**R96**] with low-fidelity models to thoroughly explore the design space and perform rapid trade-off studies, and then validation with a high fidelity model.

This multidisciplinary process, illustrated in Figure 49, incorporates models of the fuselage tail-cone zone, temperature level constraints, and mass flow requirements, allowing IAI to optimise APU cooling airflow to minimise impact on drag[49].

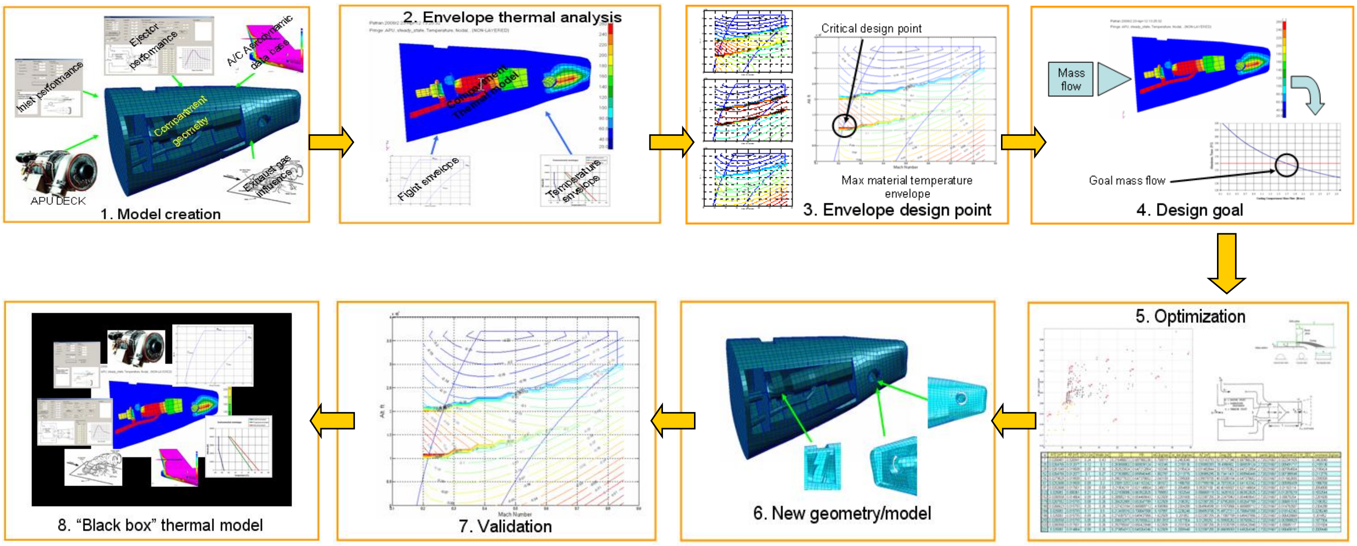

Figure 49: Auxiliary Power Unit Compartment Design Optimisation

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[49] "Auxiliary Power Unit Compartment Design Optimization", by O. Gur, J. Lewis & G. Lazar (IAI), in Proceedings of the 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, USA, 2012

3.5.3 Thermal achievements

The Global Thermal Aircraft (GTA) model **[R92]** is a novel representation of thermal behaviour at overall aircraft architecture level and provides a key enabler for a more robust specification process and improved design monitoring. This contributes to avoid any late rework of aircraft components, equipment or engines by anticipating thermal concerns early on in the concept and development phases, and thus optimizing the thermal design as a whole.

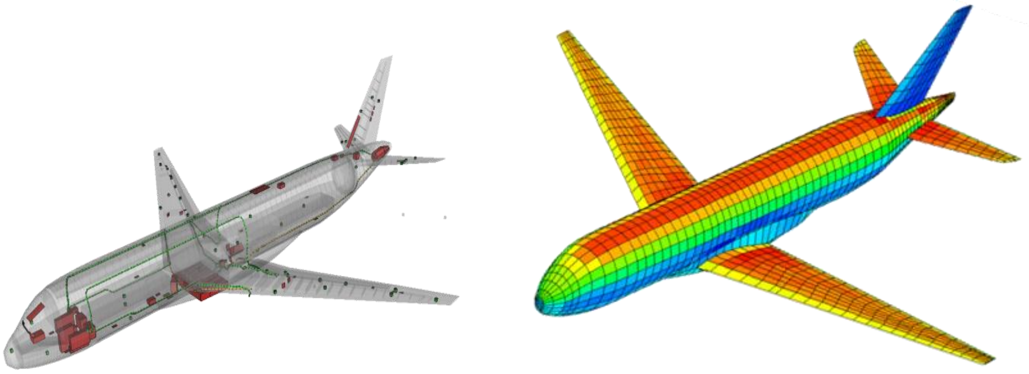

Figure 50: Global Thermal Aircraft (GTA) model

The overall aircraft design lead-time is improved by the better management of the different equipment simulation deliveries, by an integrated quality management, and also as new automated compact modelling capabilities are developed.

Architects and Experts are now supported in their trade-off activities and decisions. By practicing the new simulation processes, they will be able to adapt, stress, and challenge the planning of the simulation tasks according to their targets and through the validated fitness-for-purpose of the thermal models.

Quantified examples have demonstrated that thermal specification conservatism for electronics equipment can be reduced by 10°C for a hot sizing case, and by 15°C for MTBF. In the near future, it is expected that a more comprehensive decrease and control of the Thermal risks can be realised thanks to both the modelling & simulation advances and the collaboration capabilities from CRESCENDO.

3.6 Power Plant Integration Use Case

The Power Plant Integration (PPI) use case was used to drive the development of both BDA collaboration capabilities and specific engineering methods to improve modelling and simulation for the integration of Power Plant and Airframe design, as an overall optimised aircraft.

In addition to advanced methods for geometry and meshing preparation, aero- and vibro-acoustic modelling and simulation, optimisation and robust design strategies, and fluid-structure coupling methods reported in chapter 3.3, the following CRESCENDO integrated scenarios were addressed within the PPI use case:

- Preliminary multidisciplinary power plant design (PMPD test case S2P1)
- Distributed simulation for whole integrated power plant coupled aero-thermal model (WIPCATM test case S3P2)
- Collaborative Robust Engineering Design Optimisation (CREDO test case S3P4)

These three scenarios address challenging multidisciplinary and multi-partner collaborative design activities representative of preliminary and detailed design phases (see figure below). Additional scenarios representative of virtual test and virtual certification activities are detailed in chapter 3.7.3. A strong focus on distributed simulation and optimisation process execution, with audit traceability, quality management and process monitoring is maintained throughout, both exploiting and validating BDA collaboration capabilities.

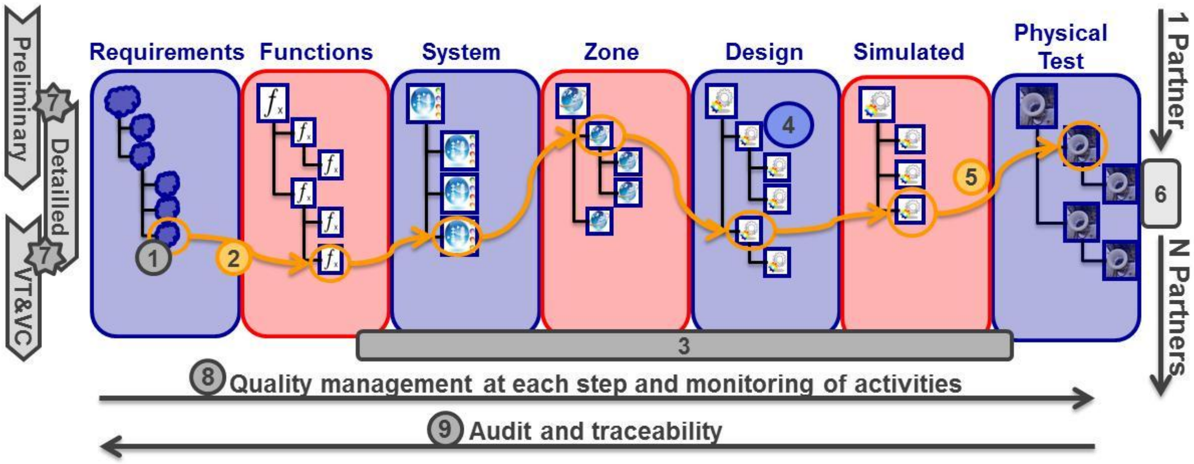

Figure 51: Power Plant Integration use case story

The following sub-sections introduce these three scenarios, then achievement is summarised.

3.6.1 Preliminary Multidisciplinary Power Plant Design

The preliminary design stage for an aircraft must not only address the optimal integrated design of the airframe and the engine individually, each with their own multidiscipline complexities, but critically must also address the multi-physics interactions between airframe and engine in order that the overall aircraft is optimally integrated. As such, co-design of the airframe and engine is essential and multiple iterations between the Airframe designers and Engine designers are required. As the definitions of each element proceeds, then focus of attention turns towards the interface between them: the Pylon.

This preliminary multidisciplinary power plant design scenario drove development of new collaborative capabilities for both optimal aircraft/engine/airframe design, and also capabilities for optimal pylon design.

Robust convergence towards the optimal design of the aircraft was demonstrated by integrating Airframe and Engine Models. The integrated models enable seeking the optimum design parameters, for example optimally balanced against specific fuel consumptions, engine weight, thrust, fan diameter and power & bleed air. Recognising that aircraft specification and design may change over time (e.g. to increased take-off mass and range), then it is also necessary to understand the consequences of such changes on optimal definition of both airframe and engine.

The upper part of Figure 52 shows the high-level process for conducting the Preliminary Multidisciplinary Power Plant Design. Mapped on the diagram are the collaborating teams that cover both the customer-supplier network as well as the extended enterprise: Airbus as the aircraft manufacturer with DLR representing its engineering enterprise; similarly, Rolls Royce and the engine manufacturer with NLR representing its engineering enterprise. The types of information being exchanged are shown as labels on the arrows; these exchanges were conducted using the BDA Collaboration Capabilities.

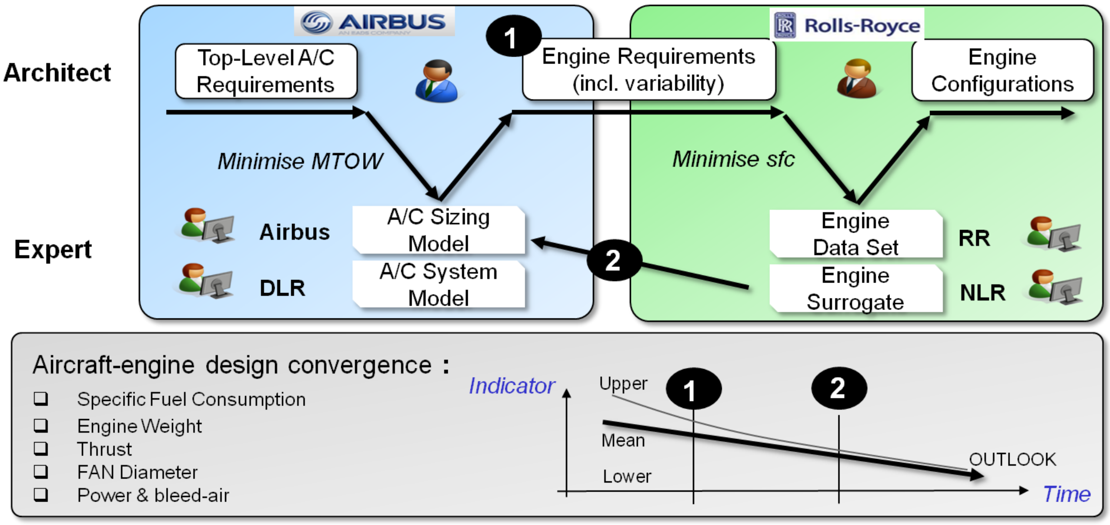

Figure 52: Preliminary Multidisciplinary Power Plant Design (S2P1)

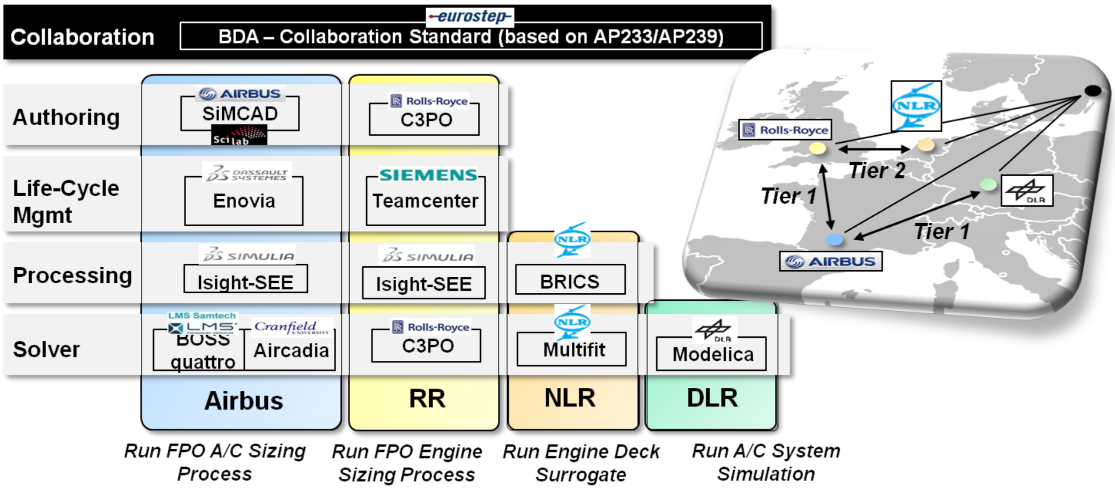

Figure 53: Tools and Platforms used by the collaborating partners

The collaborating partners had their own sets of heterogeneous environment that further tested the BDA Collaboration Capabilities (Figure 53).

The Design Convergence Maturity Indicator (lower part of Figure 52) was aggregated from the engineering parameters. This metric had a high value and a wide spread at the start of the process; as the collaborative design progressed, the metric converged to zero and the variation narrowed. This was an effective, collaborative approach to manage the maturity indicator for design convergence between Airframe-& Engine-Manufacturers, which provided an agreed basis for reaching an adequate preliminary design.

The use of surrogate modelling techniques provided a rapid data modelling capability for the aircraft designers, whilst maintain the intellectual property of the engine designers[50]. The collaborative approach showed that the number of design iterations could be reduced by 30%, thereby improving the search for the optimal airframe-engine combination.

The second aspect of the Preliminary Multidisciplinary Power Plant Design was to converge on the desired Pylon Architectures by conducting Trade-Off studies. This enabled more design solution to be considered thereby avoiding the risk of discovering “low-performing” design solutions late in the design process.

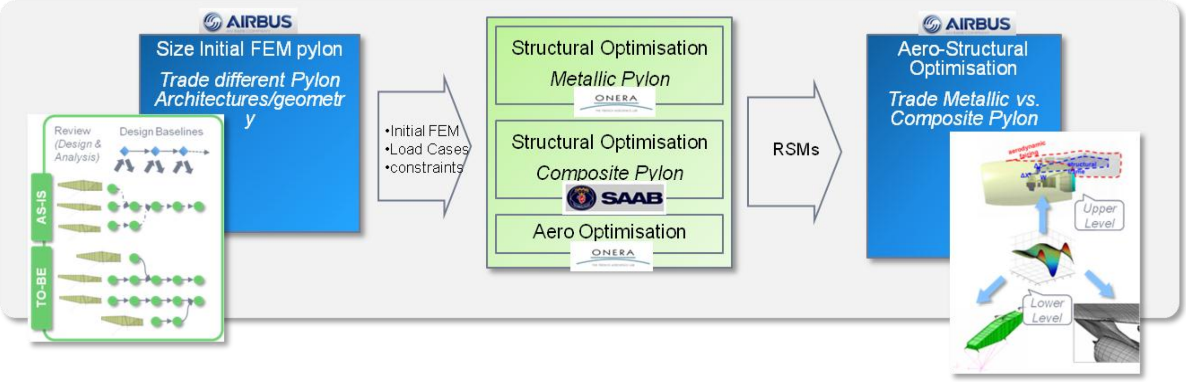

Figure 54: Pylon Architectural trades

Again a four-partner collaboration utilised the BDA Collaboration Capabilities (Figure 54) with Airbus defining the pylon requirements and conducting the aero-structural optimisation. The engineering capabilities were provided by ONERA (Paris), ONERA (Lille) and SAAB. This enabled testing the BDA Collaboration & Life-Cycle Management capabilities across the Extended Enterprise, with a traceable audit-trail.

The modelling and optimisation processes, together with the multi-scale quality check, contributed to the verification of Model & Analysis results. The results could then be used with more confidence to assess more design alternatives; wider design explorations and better manage trade-studies. Further, the use of optimised surrogate models, including response surface models contributed utilising the knowledge that resides within the Extended Enterprise whilst maintaining the respective Intellectual Properties.

3.6.2 Distributed simulation for Whole Integrated Power Plant Coupled Aero-Thermal Model – WIPCATM

The Power Plant Core Compartment is a shared area with multiple interfaces of components from different suppliers; e.g. aircraft, engine, nacelle and systems manufacturers. Across these interfaces a high number of complex thermal physics (convection, conduction, radiation) interact, each of which is studied and analysed respectively by a domain-owner. The prevailing thermal analysis of the integrated area has been performed by assembling the different components. However, this has always been a challenge, primarily due to the diversity on methods and tools used by different domain-owners to perform their thermal studies for their respective components. To overcome this challenge, a distributed simulation concept[51] is proposed to improve thermal integration activities during the Product Development Lifecycle.

In this distributed simulation concept, only the interface data (thermal results) is needed for collaborative studies (Figure 55). This helps to optimise the thermal analysis in the global design cycle, additionally it provides more reliable data based on a more robust method built on realist, shared assumptions. Such a distribution of simulations actually decouples the different analysis processes, allowing each domain-owner to apply their expertise and “best in class” methods to

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[50] “Integrate Engine Manufacturer’s Knowledge into the Preliminary Aircraft Sizing Process”, by W. Lammen (NLR) et al, at AIRTEC “Supply on the Wings” conference, 2012

[51] “Collaborative Engineering by multi-partner distributed simulation for powerplant thermal integration”, by Y. Sommerer & Q.H. Nguyen (AI-F) with G. Dubourg (SIEMENS), accepted for NAFEMS World Congress, Salzburg, 2013

create the interface data. Although, the management of the interface becomes a significant factors, it is achieved by using Simulation Lifecycle Management (SLM) capabilities.

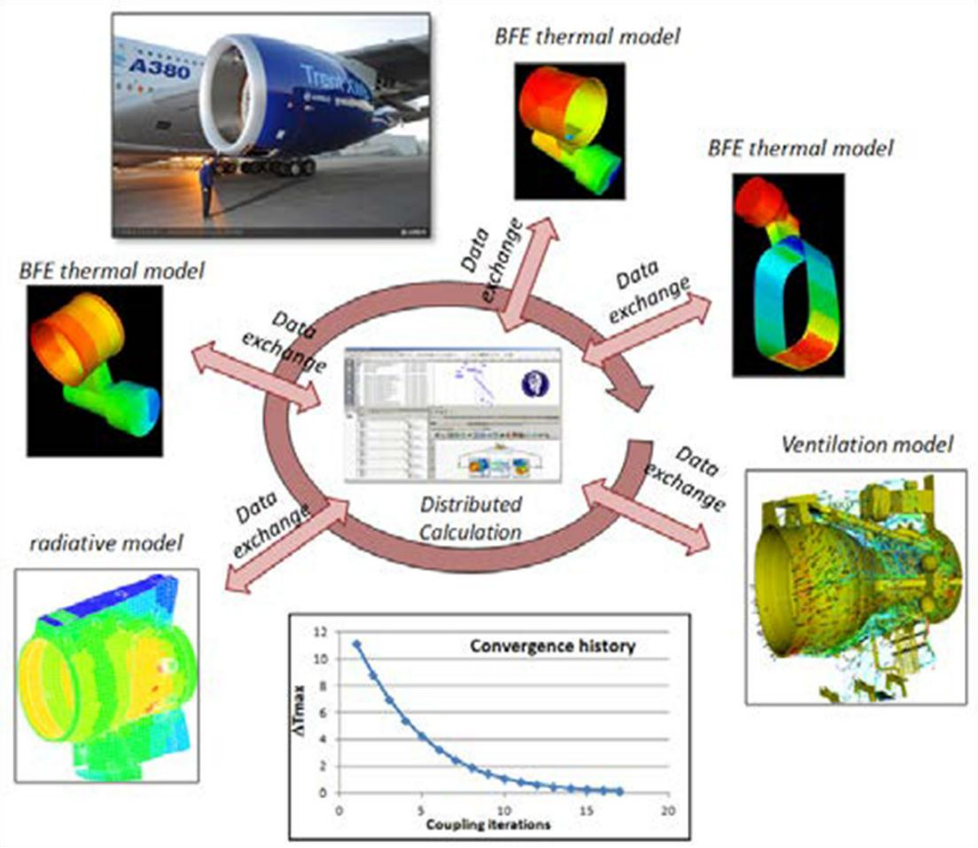

Figure 55: Distributed simulation for Whole Integrated Power Plant Coupled Aero-Thermal Model (WIPCATM)

For the final result [**R82**], industrial scale modelling & simulation activities were carried out by the industrial partners (SNECMA using DS Abaqus models, SHORTS using MSC Sinda models, and Airbus using Siemens NX models) in a truly collaborative, distributed process, see Figure 56. The interface data were exchanged over a secured protocol and an automated way, supporting the automated process in an Extended Enterprise context.

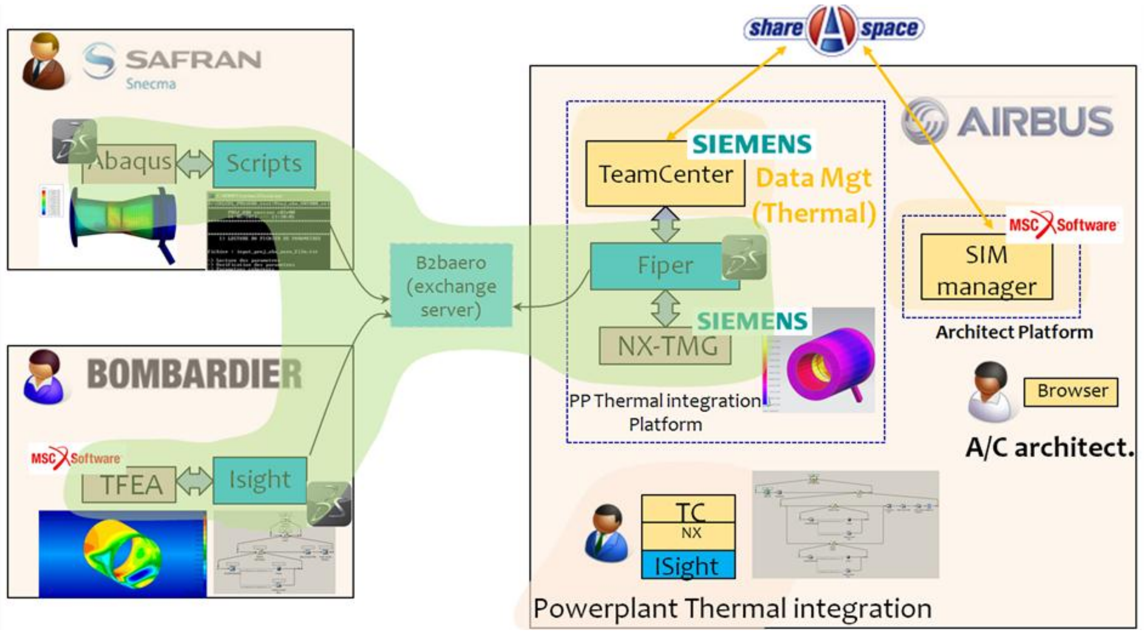

Figure 56: Industrial network setup for demonstrating WIPCATM

In addition, the whole process is supported by a global SLM environment; e.g. using Teamcenter from Siemens Software. All steps of the collaborative design cycle are tracked and managed: from architect study launch to engineering thermal analysis, including intermediate activities such as DMU extraction and CAD simplification. All steps are traceable, and can be revised to maintain the necessary links between them.

3.6.3 Collaborative Robust Engine Design Optimisation – CREDO (S3P4)

Significant results [**R2, R3, R5, R14, R21, R22, R38, R44, R105**] were achieved by the "Robust Detailed Design" test case (S3P4), to setup a **Collaborative and Robust Engine Design Optimisation** (CREDO) capability, and demonstrate application of BDA collaboration capabilities and advances in BDA engineering methods. The results have been reported in various deliverables[52] and publications[53]. Figure 57 illustrates the key features and partners involved.

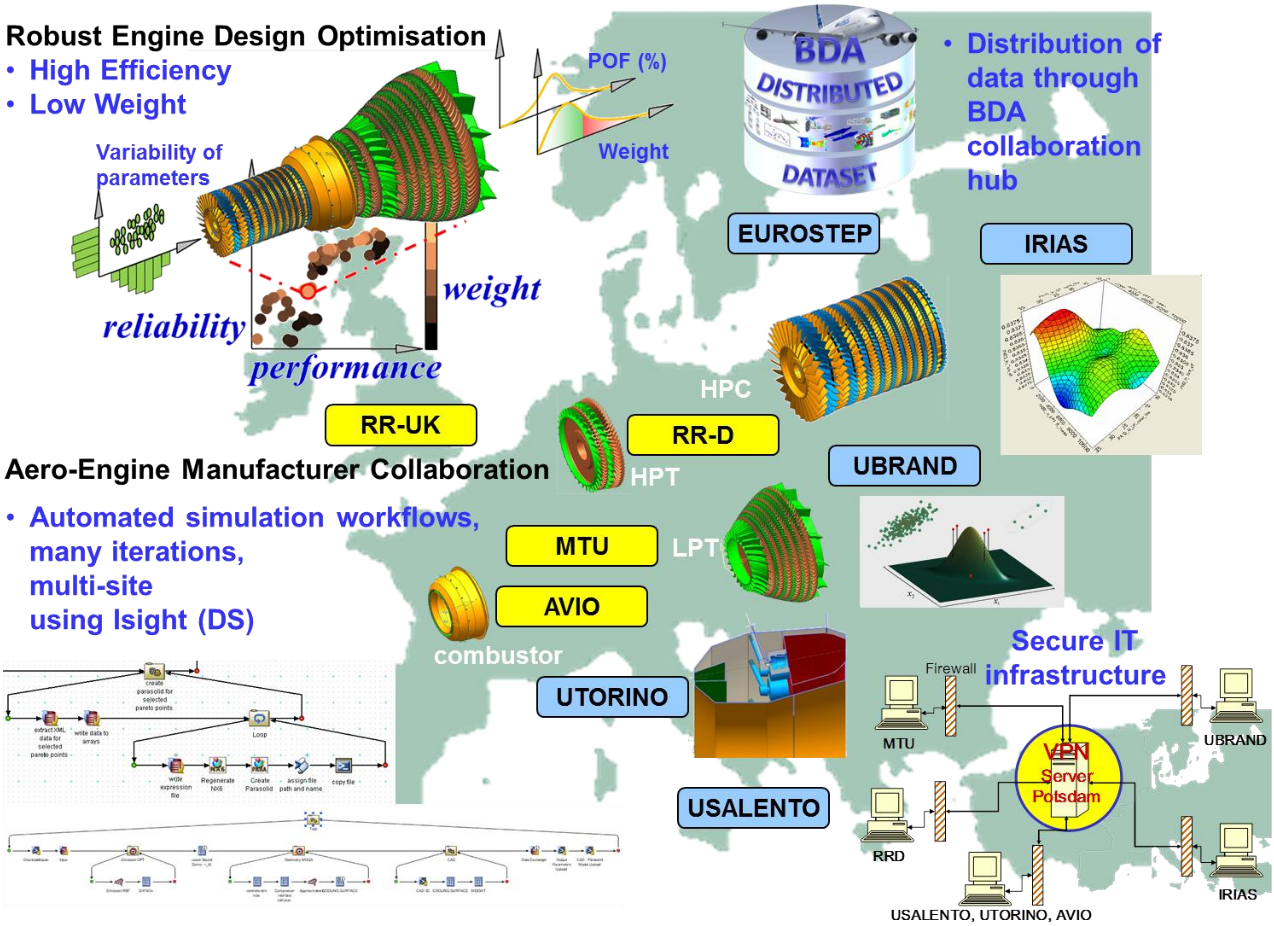

Figure 57: Collaborative and Robust Engine Deisgn Optimisation (CREDO)

The industrial partners collaborate to contribute their specific engine modules to the overall design of the engine: RR-D designs the High Pressure Compressor (HPC) and Turbines (HPT); AVIO designs the combustor; and MTU the Low Pressure Turbines. 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 optimisation of the overall engine. Hence, the CRESCENDO focus was on achieving a high degree of simulation coupling, which requires a high number of coupled design iterations.

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[52] Final results principally found in e.g. "Final definition of the translation from preliminary to detailed design phase", ALENIA et al, Deliverable D3.2.4; "Final report – capabilities for setting up a model for the detailed design phase and their contribution to demonstrations", SNECMA et al, Deliverable D3.3.5; and "Integration of Optimisation and Robust Design with the BDA, including Test Case Results", RR-D et al, Deliverable D3.4.4; and "BDA gap analysis, capabilities and results assessments", SHORTS et al, Deliverable D3.5.4

[53] E.g. "Concept for Collaborative Design and Distributed Optimisation", by M.Lockan & D. Bestle (UBRAND), in Proceedings of 5th International Conference from Scientific Computing to Computational Engineering (IC-SCCE), Athens, 2012; and "Collaborative Robust Engine Design Optimization", by R. Parchem & P. Flassig (RR-D), H. Wenzel (DS), accepted for SIMULIA Community Conference, Vienna, 2013.

The two objectives of the optimisation, to achieve an engine with best efficiency and lowest weight, are also shown in a simplified way in the top left of Figure 57. This takes into account uncertainties and variability (e.g. of design parameters), until a stable region of the design can be found to ensure the robustness (i.e. probability of failure to meet the objective is very low). The results were achieved with the advances in fast optimisation and robust design methods developed together with IRIAS, UBRAND, UTORINO & USALENTO (see 3.3.3 and 3.3.4).

Three main BDA collaboration results (see 3.2.1 and 3.2.2), indicated in Figure 57, enabled the collaborative execution of these optimisation and robust design studies:

- The IT infrastructure was setup to connect the simulation environments with consideration of each partner's network security and IPR constraints.
- For both the preliminary design data (generated using the Rolls-Royce CP3O engine performance optimisation) and the robust detailed design phase, the data distribution was enabled through the BDA collaboration hub (provided by Eurostep) and specific web services written by the collaborating partners.
- High frequency process-driven workflows were designed and executed, using Isight/SEE (DS) as a common solution to execute the tightly coupled simulations, with many iterations across the multiple sites.

The following conclusions were made:

- Before CRESCENDO, collaborative design optimisation was inefficient, slow and only sub-optimal, with no robustness assessment of the whole engine system.
- With the CRESCENDO results, collaborative design optimisation is improved, with efficient data sharing, flexible interfaces between sub-systems, and more intelligent optimisation in a collaborative IT-network. In short, Robust Design is now possible.
- Automated design simulation workflows provide a solution to reduce the engine development lifecycle duration and cost.
- Advances in enabling optimisation and robust design earlier in the lifecycle provide a solution to prevent expensive rework.

3.6.4 Power Plant Integration achievement summary

A global improvement on managing Power Plant integration activities is demonstrated throughout the Power Plant CRESCENDO Test Cases. Many improvements on engineering challenges are demonstrated (through optimisation, management of multi-level views of the product, improved engineering methods as for meshing…) and are promising technologies so as to reach a new level of maturity on how Power Plant is designed and optimised. Many industrial constraints have also been solved regarding collaboration for example (use of the BDA Object model for exchanges, real exchanges with MTU…). And finally, many business methods have ensured to increase design maturity and can be now exploited into the industry (such as for the whole aero-thermal virtual engine…).

CRESCENDO has enabled to make a new step into the development of useful capabilities (for engineering, business and collaboration) to improve the way product is engineered, shared… It's then expected to go further in the "real industrial life" on applying such technologies on future programs to enhance the competitiveness of the European aeronautical industry.

3.7 Virtual Testing Methodologies & Applications

In CRESCENDO, Virtual Testing (VT) has been understood to mean the use of computer simulations for critically assessing the product design against specified requirements. These simulations, integrating design models and design parameters, produce information sources for decision making. Virtual tests follow the same rules (and face the same challenges) as Physical (i.e. Real) tests in terms of data management, levels of confidence, estimation of errors, uncertainties and product Verification & Validation (V&V).

For the case of certification, the requirements are stated by certification authorities, typically the European Aviation Safety Agency (EASA). Hence, Virtual Certification (VC) refers to using Virtual Testing as an Acceptable Means of Compliance (AMC) in certification.

The CRESCENDO results for VT & VC contribute to:

- Reducing test costs by the use or reuse of simulation capabilities as an acceptable and cost-effective means to minimise extensive, expensive and sometimes dangerous physical test campaigns; also reduces risk associated with physical hazards by the use of simulation;
- Optimizing the number, extent & quality of physical test campaigns through better anticipation of the behaviours to be tested;
- Increasing the credibility and fitness-for-purpose of modelling to improve the use of simulation in the certification process.

The CRESCENDO results provide an overall guiding methodology and process for VT & VC together with the specific processes and related methods that were principally demonstrated in three test cases. These include developing VT capabilities for energy (e.g. electrical) systems modelling (S4E1); power plant simulation supporting virtual certification (S4P2); and thermal equipment qualification (S4T1). A fourth test case was concerned with simulation methods for noise prediction from aero-acoustic behaviour of jets and this is reported more appropriately within the chapter on BDA engineering methods results. All these results have been documented[54] and made available as a training module in the BDA e-Learning portal (see chapter 4.8). A qualitative analysis was performed[55], concluding that 77% of the VT test cases scenario objectives had been partly or fully covered. Some of the main results are summarised in the following paragraphs.

3.7.1 VT methods and general process for Virtual Testing & Virtual Certification

An overall Virtual Testing methodology view[56] was derived within CRESCENDO, shown in Figure 58. This is based on five key methodological areas that support the use of modelling & simulation in Virtual Testing: (1) Systems Engineering approach for VT & VC, including reference to the generic process described below, and overall VT architecture definition; (2) Pre-processing chain i.e. setting up the automatic generation of simulated results using test data parameters; (3) Correlation processes for data comparison, quality measurement and models validation; (4) Model integration methods including surrogate modelling and uncertainties management, and related technical standards for model coupling such as FMI (Functional Mockup Interface), Modelica as a language to describe dynamic systems; and SysML as a language to describe model integration; (5) share test and simulation data i.e. linking data from heterogeneous information systems, and ensuring traceability of data in a VT studies (includes link with BDA collaboration capabilities). The figure also shows a functional view developed with the VT methodology, intended to give a picture of 6 key functions related to performing Virtual Testing studies with BDA platforms implementations. In addition, the figure shows some examples of how the scope of the developments[57] and selected demonstration scenarios for related VT Test Cases have been mapped to the key methods areas and functional views.

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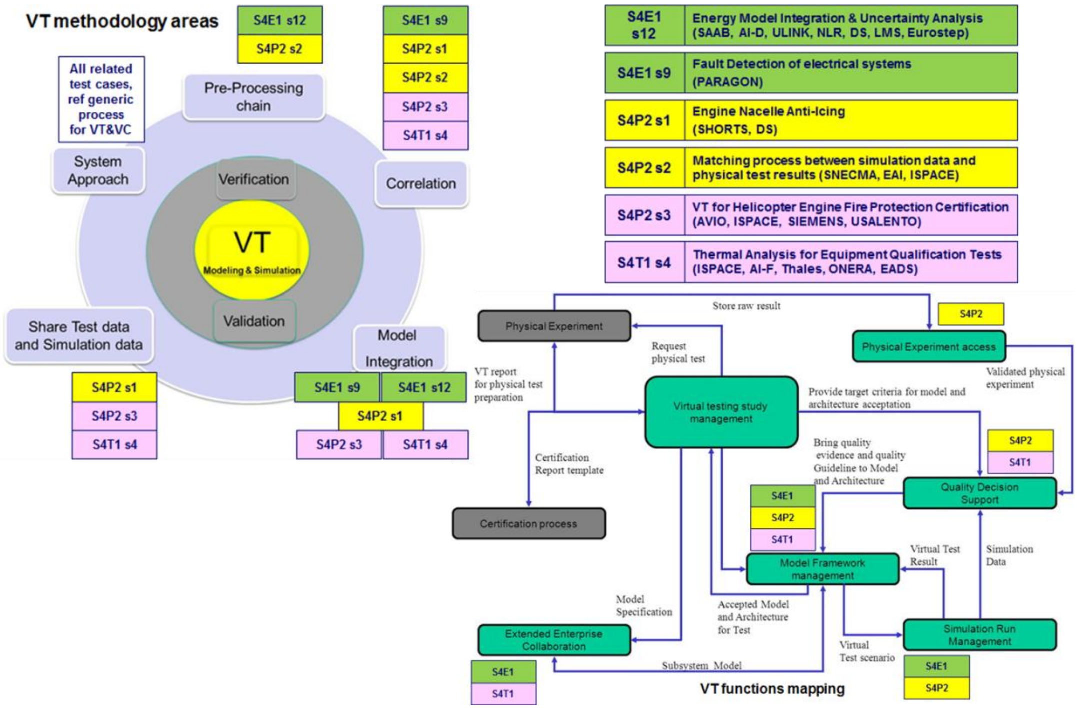
[54] "VT&VC Test cases demonstration and evaluation", ECPTR et al, Deliverable D4.4.4

[55] "SP4 Demonstration Results Synthesis", SAAB et al, Deliverable D4.1.2

[56] " Virtual Testing methodology for aeronautic development ", EADS et al, Deliverable D4.2.1

[57] "Developments made for the "Full" demonstration", ECPTR et al, Deliverable D4.2.4



S4E1 s12	Energy Model Integration & Uncertainty Analysis (SAAB, AI-D, ULINK, NLR, DS, LMS, Eurostep)
S4E1 s9	Fault Detection of electrical systems (PARAGON)
S4P2 s1	Engine Nacelle Anti-Icing (SHORTS, DS)
S4P2 s2	Matching process between simulation data and physical test results (SNECMA, EAI, ISPACE)
S4P2 s3	VT for Helicopter Engine Fire Protection Certification (AVIO, ISPACE, SIEMENS, USALENTO)
S4T1 s4	Thermal Analysis for Equipment Qualification Tests (ISPACE, AI-F, Thales, ONERA, EADS)

Figure 58: Key areas of VT methodology & functions covered by selected CRESCENDO results

CRESCENDO proposes **[R98]** a structured and repeatable generic process[58] with associated guidelines[59], for the introduction of Virtual Testing as an Acceptable Means of Compliance (AMC). This is based on the established certification process as defined by the European Aviation Safety Agency (EASA), but as EASA was not directly involved, the concept has been validated only in an industrial context.

The top level view of the process is shown in Figure 59. The whole process can be divided into four main phases, managed by a Certification Team composed by members of the Applicant and members of the Authority. At the Applicant level, the red marked activities identify the main focus for the CRESCENDO VT & VC application results, and these sub-processes have been described in deeper levels of detail. For example, "Define Acceptable Means of Compliance (AMC)" is the core process to define, develop, propose and validate the VT architecture to be used as AMC in the certification. Main outputs from this sub-process are 1) the VT architecture accepted by the authority as a means of compliance, and 2) the Type Certification Programme.

Main partners involved in developing these results: EADS, SAAB, ECPTR, AVIO, ULINK

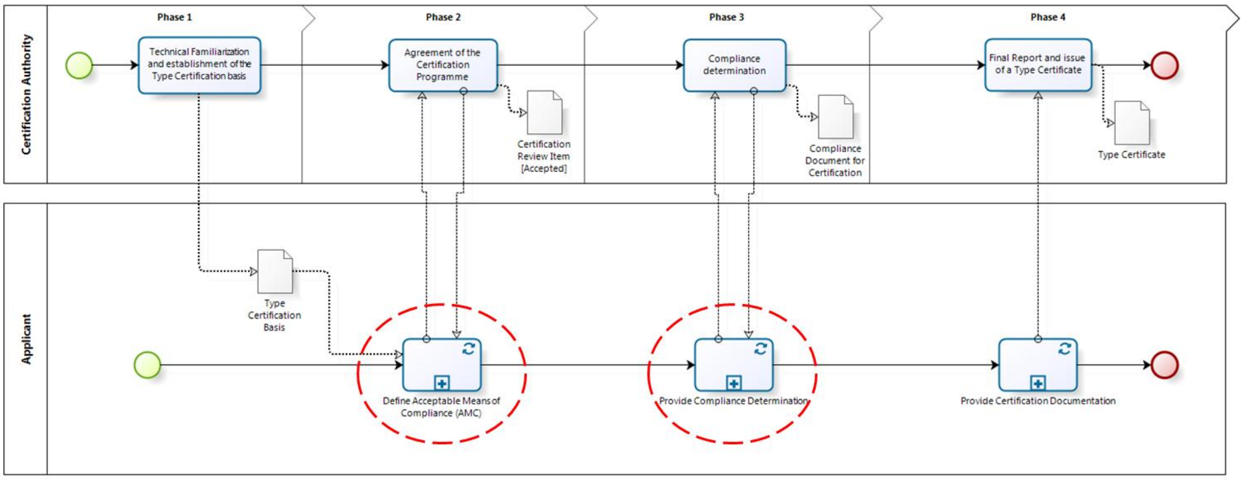


Figure 59: Generic Process for VT & VC (top level view)

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[58] "Requirements enabling Virtual Testing as Acceptable Means of Compliance for Certification", GKNAES et al, Deliverable D4.3.3

[59] "Guidelines for use of Virtual Testing as Acceptable Means of Compliance for Certification", SNECMA et al, Deliverable D4.3.4

3.7.2 Example results for Virtual Testing of Aircraft Systems behaviour

Overall, the “Energy System Virtual Test up to Certification” test case (S4E1) addressed several problem areas in aircraft and helicopter energy systems modelling and simulation. The models used are derived from environmental control systems and electrical systems. The typical problems investigated also occur for other fluid mechanical systems e.g. fuel and hydraulic systems, but often with stiffer characteristics. The final feasibility has been assessed in four demonstration scenarios and main results from two of these are summarised here.

Energy Models Integration and Uncertainty Analysis

This scenario **[R85]** is illustrated in Figure 60 and used an aircraft systems example to demonstrate how to share models and results from different tools, perform virtual tests and gain knowledge and confidence about the accuracy of the results. The partners involved (SAAB, AI-D, ULINK) used the Share-A-space hosted BDA collaboration hub to share a combination of models i.e. Consumer (Acceleration Dependent Pressure Regulator or ADPR), a simple Environment Control System, and a full Cabin air system. Two main methods were used.

- **Model integration** was performed using the **Functional Mock-up Interface** (FMI), as a tool independent standard to support both model exchange and co-simulation of dynamic models using a combination of xml-files and compiled C-code[60]. FMI originated in the MODELISAR[61] project and allows models to communicate by standardizing inputs and outputs. FMI also enables the sharing of ‘black box’ models with intellectual properties belonging to different stakeholders.
- **Uncertainty analysis** is a method to increase the understanding of how model parameters are linked to each other and to assess how uncertainties in system models and their parameters affect the credibility of the results. Uncertainty measures can be used for test planning and revealing where to put further modelling effort.

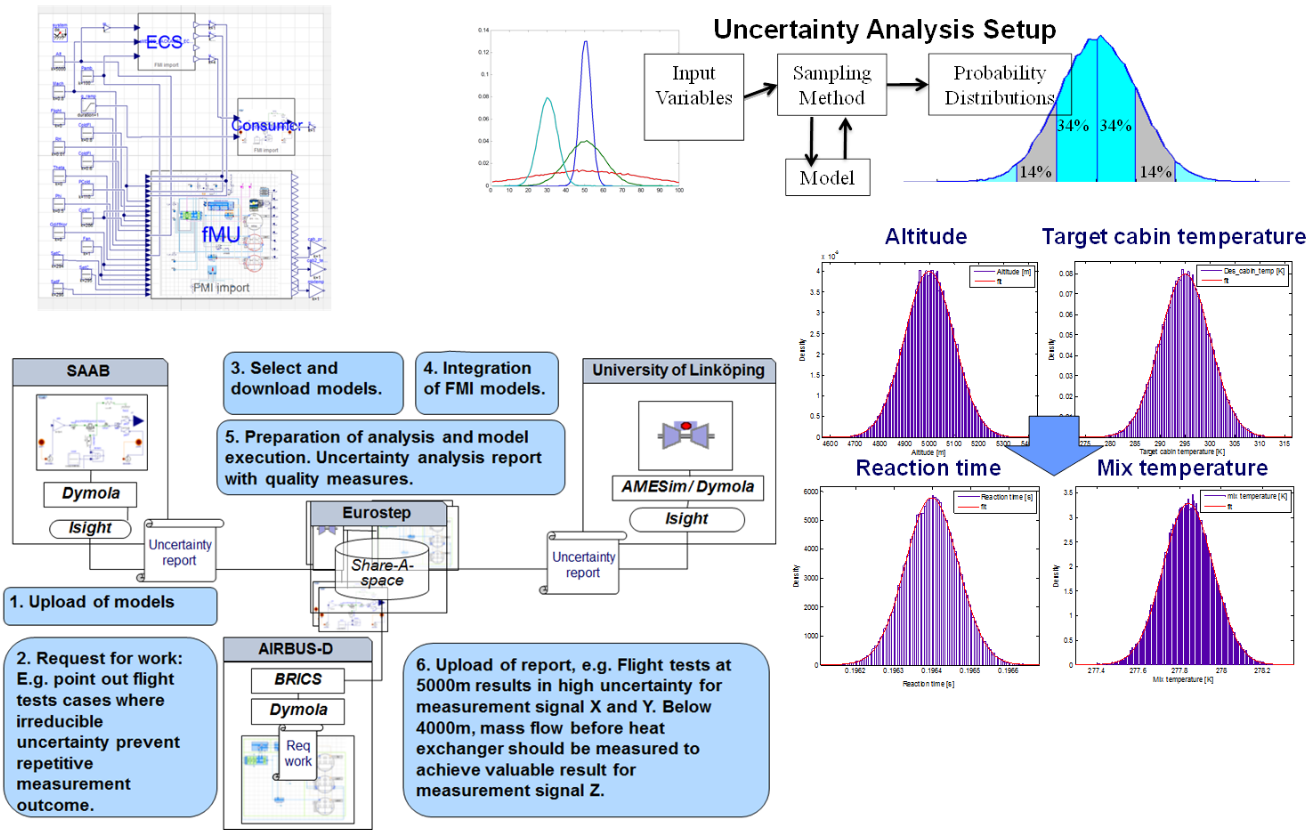

Figure 60: Aircraft systems Models Integration and Uncertainty Analysis results

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[60] See https://fmi-standard.org/

[61] MODELISAR was an ITEA 2 (Information Technology for European Advancement) European project aiming to improve the design of systems and of embedded software in vehicles, see http://www.itea2.org/project/index/view/?project=217

Different methods[62] for propagating uncertainties from the model and its inputs to its outputs were evaluated: Monte-Carlo simulation of the ADPR model with 20,000 samples, Latin Hypercube Sampling (LHS) of the ADPR model with 50 samples; Monte-Carlo simulation with the ADPR model replaced by a second-order response surface; and the LHS using the response surface. The set-up and resulting probability distributions from the uncertainty analysis are also shown in Figure 60.

The following conclusions and operational benefits have been found:

- Uncertainty analysis can reduce the number of physical tests and improve their quality;
- Uncertainty analysis can support the model verification and validation phase;
- Methods for uncertainty propagation and evaluating robust designs support the virtual system certification by estimating the variability of the model output;
- The Functional Mockup Interface enables models integration, which leads to shorter time until assessment of system performance and behaviour, while intellectual properties are preserved. FMI is a promising standard and implemented into thirty or more tools. A somewhat improved control of intellectual properties e. g. customer specified black-boxes are desired.
- Model sharing via BDA collaboration capabilities enables organized model handling e.g. version control. The connections using the BDA platform and the scenario concerning notification of "request for work" as well as model downloading with traceability were presented.

Fault Detection process towards validation of simulation data for electrical systems

This result **[R65]** concerns the demonstration of an electrical system fault detection tool[63] developed by PARAGON. The objective is to provide independent validation (i.e. outside the electrical network simulation suite), via the BDA collaboration platform, **ensuring that the measurement data from virtual tests involving electrical network models have been produced by a fault-free environment**.

The process is illustrated in Figure 61, also showing a graphical example of the fault simulation data used, and is composed of three main steps:

(1) Identification and initialization of fault implementation in available electrical network models of subsystems providers; (2) Simulation of fault and non-fault modes with electrical systems models; and (3) System Integrator detection of the location of specific faults through implementation and training of the Neural Network (NN) of the fault detection tool.

The mode of operation and functionality of the developed fault detection tool was demonstrated by its application on aircraft electrical models developed in SABER (outside CRESCENDO) and comprising of: a variable frequency starter generator (GEN); Electromechanical Actuator (EMA); Wing Ice-Protection System (WIPS); and two Primary Electrical Power Distribution Centers (PEPDC), to protect the EMA and WIPS feeders. The following conclusions were made:

- The fault detection tool concept was applied successfully, with ~**100% accurate detection** for all faults induced in the electrical network examined;
- The tool is **robust** i.e. data degradation was overcome successfully, and **adaptable** i.e. various topologies allow for a tool that can be adapted to detect & locate all faults under uncertainty conditions;
- Independent verification of error-free simulation environment; improves quality and reduces number of physical tests needed to validate the measurement data.

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[62] "Comparison of Sampling Methods for a Dynamic Pressure Regulator", by J.A. Persson & J. Olvander (ULINK), at 49th AIAA Aerospace Sciences Meeting, Florida, USA, 2011

[63] "Fault detection of electrical systems towards validation of simulation data", by J. Tsahalis (PARAGON) et al, at 5th SCCE International Conference, Athens, 2012

In terms of exploitation, PARAGON plans to further extend the fault detection tool for general use in design and certification, also for operational aircraft fault detection during flights.

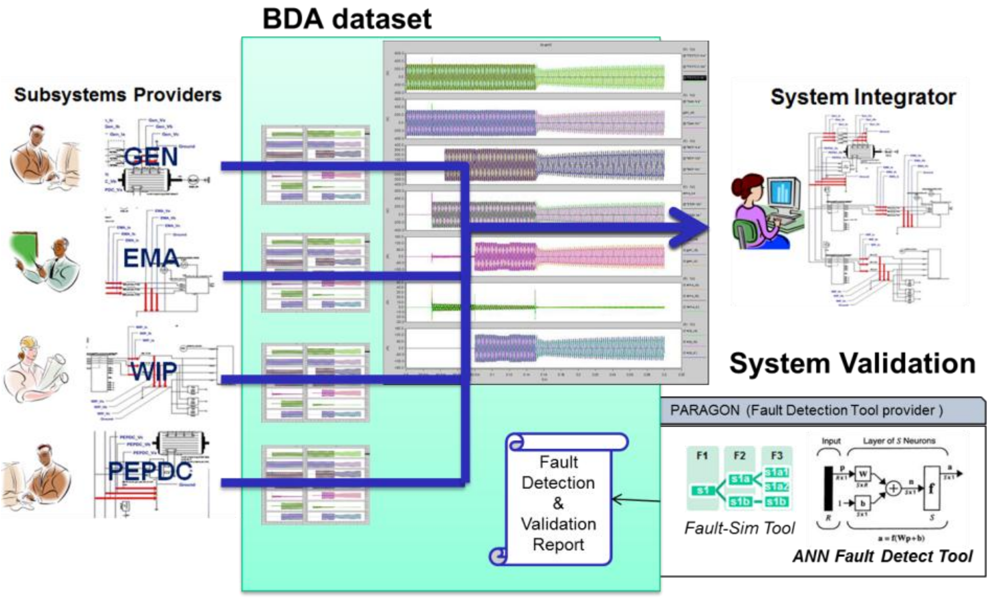

Figure 61: Fault Detection process for Electrical systems simulation

3.7.3 Example results for Virtual Testing of Power Plant behaviour

The overall “Simulation for Certification” test case (S4P2) delivered results to improve the use of simulation during the tests required in the product certification process related to Power Plant, as defined mainly in the CS-E (Certification Specification for Engines). The results support the following three specific scenarios.

Engine Nacelle Anti-Icing

This first scenario concerns compliance of nacelle anti-icing systems to “CS-25 paragraph 1093 Air intake system de-icing and anti-icing provisions” and “CS-25 paragraph 1419 Ice protection”. The results [**R36**] produced by SHORTS include accurate and correlated models and an associated matching process (developed with DS using Isight), with automated graphical reporting to make an immediate assessment of the quality of experimental measurements and analytical values. SHORTS estimate up to 30% time saving in dry air flight test data analysis.

Matching process between simulation and physical test results for engine performance

The second scenario was provided by SNECMA and concerns compliance of the power plant (engine with its nacelle) to “CS-E paragraph 790 Ingestion of Rain and Hail”.

For virtual testing in this scenario, the result [**R37**] is a data reduction process implemented in DynaWorks (ISPACE) together with an engine deck[64] from the PROOSIS performance analysis software (from EAI). The process includes the following steps:

- Data validation: test data are recovered after the ground test and are sorted in order to remove incorrect data (e.g. faulty sensor). A 1D vector is then generated (DynaWorks).
- Data matching: the 1D vector relating the behaviour of the engine during the test is compared to the performance simulation results from PROOSIS. Then, two phases are possible. The first uses the engine deck within DynaWorks to identify the gap coefficients between the physical test and simulation (virtual test) results. The second one does the matching directly in PROOSIS, in this case being able to re-adapt the engine model in order to have more accurate results for the next tests.

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[64] An engine deck is a simulation model generated by PROOSIS and able to run as a black box and in stand-alone mode.

- Post-treatment: for instance, displaying the evolution of one parameter according to several points during the test; or comparison of the same point during different days of test.

The process itself has proved its feasibility and usefulness through many engine developments, and the innovation lies in using DynaWorks for the data reduction and the interoperability with PROOSIS. The main advantage for SNECMA is to have a simple, fast and robust data matching process for common use in all the engine programs.

Virtual Testing for a Helicopter Engine Fire Protection Certification

The third scenario concerns compliance of engine subsystems to “CS-E paragraph130 Fire Protection”, using a helicopter engine gearbox example provided by AVIO. This scenario advances the use of simulation for compliance to CS-E 130 specification for fire protection (as prescribed by EASA AMC-130). This requires exposure of engines or engine sub-systems to fire for 15 minutes, and is the most critical and expensive part of the certification.

As shown in Figure 62, the results are improved fidelity of the transient thermal simulation of the engine fire test scenario (including exposure for 5 minutes at engine idle conditions, and 10 minutes at engine windmill), and a multidisciplinary virtual testing process. This is an example implementation of the “Develop and Validate VT architecture” sub-process inside the general VT & VC process proposed by CRESCENDO (see chapter 3.7.1).

To implement the process [**R99**], a prototype software platform was set-up at AVIO and USALENTO. This uses Teamcenter (SIEMENS) for managing the thermal simulation process, models and results. Central in the process is the connection [**R100**] to an external platform, DynaWorks (ISPACE). This tool extracts data from the thermal simulation files and performs the correlation with the historical physical test data.

The process performed is fully auditable, with traceability of the generated data during execution, and quality gates are introduced (supported by the dashboard concept described in chapter 3.2.3), to validate both the simulation results and correlation with test data.

The result is a step towards proposing the simulation as an Acceptable Means of Compliance, and hence to reduce the number and scope of the real tests required for certification.

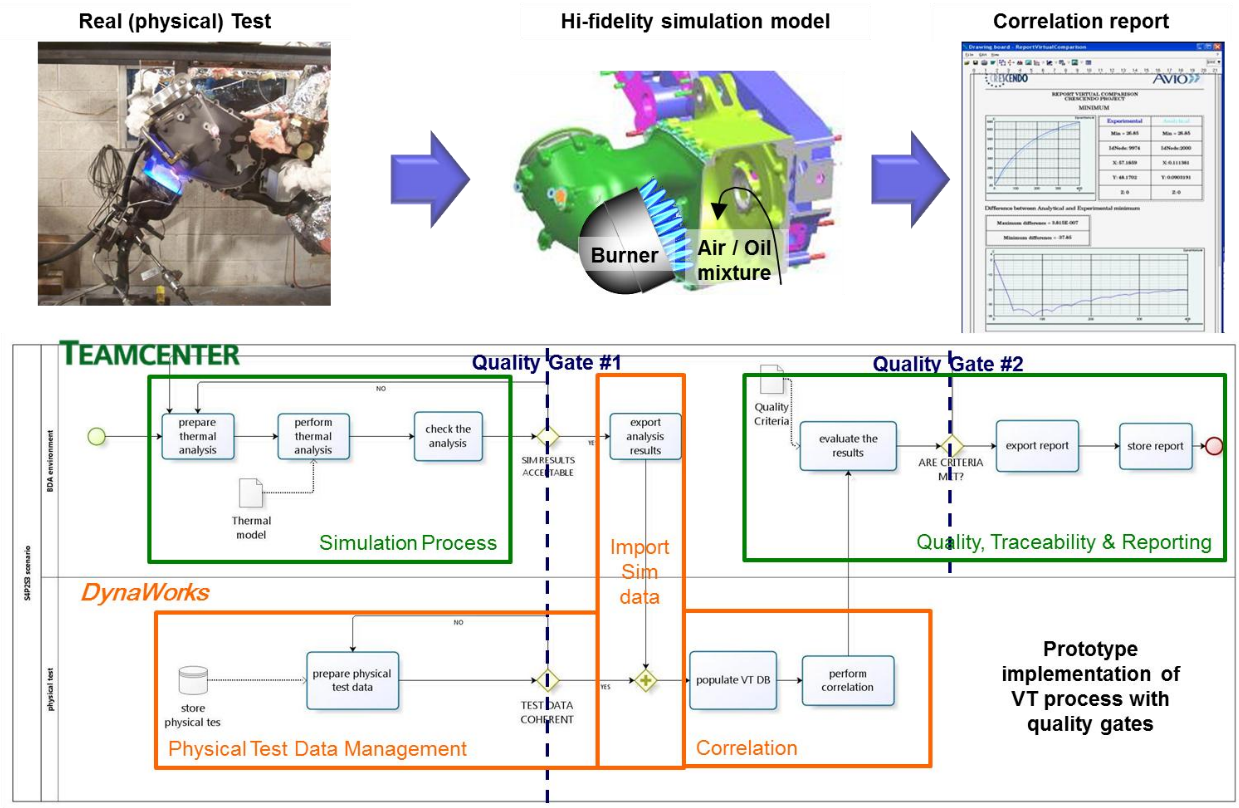


Figure 62: Virtual Testing process for engine fire protection certification

3.7.4 Example results for Virtual Testing of Thermal Behaviour

The “Thermal Certification & Qualification” test case (S4T1) focussed on virtual testing methods for the qualification of airborne equipment and analysing the compliance to environmental temperatures specifications. For equipment qualification, the supplier has to demonstrate that their equipment operates in the environmental conditions encountered in airborne operation. Today, these qualification processes are mainly done by experimental tests, specified by the DO160 standard for environmental testing.

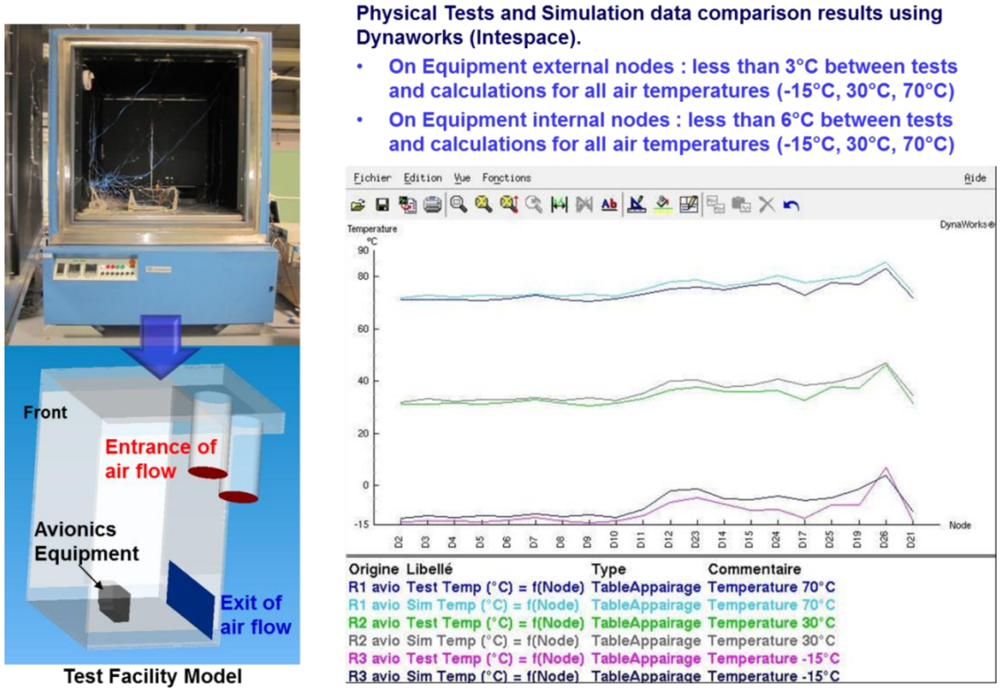
The main result highlighted here [**R94**] is a climatic chamber virtual testing capability developed by ISPACE, and its use to virtually test and validate the behaviour an example avionics equipment model provided by THALES. This was linked with other test cases and formed the final stage of the overall equipment thermal design and integration process (see chapter 3.5.2) to establish a new way of working with suppliers and use the Global Thermal Aircraft (GTA) model as an integration tool.

- The first step was to develop & validate a model of the large climatic test chamber used for the qualification tests, shown in Figure 63. This was done using SIEMENS TMG and NX Flow.
- The next challenge was coupling the nodal model of the avionics equipment with the model of the test chamber. The avionics equipment model was developed by THALES and delivered as a compact Equipment Neutral Thermal Model (ENTM, see chapter 3.5.2) in Minitan format.
- A good comparison (see Figure 63) was achieved between recorded physical test data and the combined chamber & equipment virtual test data in order to validate the ENTM of the avionic equipment.

The anticipated impact of this result will be to de-risk the qualification of equipment and to use the validated equipment model in order to predict its behaviour in worst case flight conditions.

This scenario also used BDA quality methods and CAS dashboard (see Figure 19 in chapter 3.2.3) within virtual testing and carried out 3 checks with 2 quality gates: one for each step above.

Main partners involved: ISPACE, AI-F, THALES, EADS.



Physical Tests and Simulation data comparison results using Dynaworks (Intespace).

- On Equipment external nodes : less than 3°C between tests and calculations for all air temperatures (-15°C, 30°C, 70°C)
- On Equipment internal nodes : less than 6°C between tests and calculations for all air temperatures (-15°C, 30°C, 70°C)

Origine	Libellé	Type	Commentaire
R1 avio	Test Temp (°C) = f(Node)	TableAppairage	Temperature 70°C
R1 avio	Sim Temp (°C) = f(Node)	TableAppairage	Temperature 70°C
R2 avio	Test Temp (°C) = f(Node)	TableAppairage	Temperature 30°C
R2 avio	Sim Temp (°C) = f(Node)	TableAppairage	Temperature 30°C
R3 avio	Test Temp (°C) = f(Node)	TableAppairage	Temperature -15°C
R3 avio	Sim Temp (°C) = f(Node)	TableAppairage	Temperature -15°C

Figure 63: Virtual Testing of Climatic Chamber for Avionics equipment thermal qualification

4 Potential impact, main dissemination activities & exploitation of CRESCENDO results

4.1 Introduction

The CRESCENDO project has been a collaborative team effort and the impact of the results, for the benefit of society as a whole, is secured at several levels.

The consortium partners, broader aeronautical community, and next generation aircraft programs will benefit from the demonstrated CRESCENDO **innovations in collaborative modelling and simulation to deliver the Behavioural Digital Aircraft**, throughout the **product development process** and across the **extended enterprise.**

CRESCENDO enables the creation of the **BDA dataset**, with new processes and methods:

- To provide a methodology for value-driven design to meet stakeholders expectations;
- To eliminate risk early in preliminary design and more accurately predict the detailed operational and functional behaviour through architecture trade-offs, sophisticated multi-physics analysis, robust multidisciplinary design and optimisation strategies;
- To provide a virtual testing methodology to reduce the need for repeat physical testing and prepare for certification based on simulation.

CRESCENDO enables interoperable **BDA platforms** and supports the **BDA enterprise**, with new engineering analysis software functionalities and real collaborative product development capabilities for multiple partners and multidisciplinary teams working across the extended enterprise.

Such innovations in the aircraft product development process are key factors to sustaining competitive business performance for the industry & supply chain, and to meeting the challenges from the market and society.

Progress in the months following CRESCENDO indicates that the BDA vision is becoming reality in the industrial partners' context, is reflected in the software vendors' solution roadmaps, and is reaching more potential adopters beyond those involved directly in the project. The academic institutions involved also have a role to play in terms of passing the knowledge gained onto the next generation of engineers.

The remaining chapters of this report elaborate on these impacts in more detail, in terms of the aeronautics industry, software vendors community, standardisation strategy, and future research. How the CRESCENDO project measured its progress towards objectives is described, as well as the ways that the results have been disseminated and are made available for exploitation by the consortium, the wider aeronautics supply chain and related scientific community.

In brief, the dissemination and exploitation actions include the main **CRESCENDO Forum** (and **handbook**) held in June 2012 with 300+ participants, four other industry supply chain events, and more than **90 conference** or **journal publications**; the creation of a **catalogue outlining more than 80 exploitable results** and the **BDA e-Learning portal** for the consortium; and **100 final deliverable documents**.

Further information will be found on the CRESCENDO **public website**: www.crescendo-fp7.eu. At the time of writing, an update of the public website was still required to include all finally agreed publishable results and provide a legacy version. When completed, the public website will remain live for a minimum of three years after project end i.e. until end October 2017.

4.2 Aeronautics Industry Impact

In this report, it is not possible to elaborate on the impact of the CRESCENDO results for all of the individual industry partners engaged in the consortium, but a few examples of the major outcomes and exploitation plans reported at the Final Review[65] are included below.

Within **Airbus**, the CRESCENDO results and the follow-on projects are a key part of the overall Process, Methods & Tools (PM&T) technology roadmap to deliver a complete "Virtual Aircraft" capability. In CRESCENDO, Airbus took the lead in developing the overall BDA architecture and is one of the main authors of the BDA Business Object Model, as well as improving modelling & simulation capability through participation in 12 of the 17 test cases. The path towards full operational exploitation is first to bring the on-going research to TRL6 maturity for Airbus purposes; and then to prepare the M&T program for industrialisation, with a global target to have M&T ready in the coming years to support development of future or derivative aircraft. CRESCENDO has delivered the foundations (the status of internal Airbus TRL assessment at the end of the project is indicated) for a next generation collaborative platforms environment (TRL4) using COTS-based solutions to enable more flexible & efficient architecture trade-offs and distributed multi-physics modelling & simulation across the extended enterprise; providing a first global aircraft-level thermal evaluation (TRL3), improved power plant evaluation capabilities (TRL4), and basis for a future virtual & hybrid testing framework (TRL2).

Within **Eurocopter**, there is support from PM&T stakeholders and decision makers to develop an overall simulation data management approach based on CRESCENDO results. The overall BDA architecture has been assessed at TRL3 for Eurocopter purposes. Some key results for Eurocopter come from work in the WIPCATM[66] test case where a flexible weak-coupling collaborative workflow has been established for engine and compartments CFD and thermal models; where surrogate modelling using the MACROS[67] toolset (developed with IRIAS during CRESCENDO) has been validated as feasible using real (but limited) data; and where benefits are seen for rapid preparation of geometry for analysis using Siemens NX Synchronous Technology[68].

For **EADS** as a whole, the impact has been the awareness and increasing interest in the outcomes of CRESCENDO across the business units that did not participate directly in the project (i.e. **Astrium** Space Transport & Satellites, **Cassidian** and **MBDA**), as well as the ones that did (i.e. Airbus, EADS-IW and Eurocopter). Starting with the CRESCENDO Forum, this has grown through on-going communication and interaction with the EADS PHC (PLM Harmonisation Centre) and its constituent network of projects, where multiple business units work together, with a current focus on key PLM areas such as Systems Engineering, multidisciplinary simulation & optimisation.

The main business impacts seen by **Alenia Aermacchi** are: reduced lifecycle time, particularly for performing trade-off studies with reduced non-value adding manual processes; improved information exchange between disciplines and across the supply chain to achieve the right architecture choices first time; and reduction of physical testing by ensuring high quality simulation results. Some key results for Alenia are from the GTA[69] test case: working together with AI-F, Eurostep, Paragon, MSC & USALENTO in particular, this demonstrated process automation with CAD-CAE integration, and optimisation of thermal systems (e.g. Environmental Control System) and air system components, including from a cabin passenger comfort perspective. However, Alenia considers that industrial level deployment will still require big efforts in standardisation, training and change management.

The potential impact for **Rolls-Royce** is improved engine design with nacelle & aircraft integration, providing reduced development cost and environmental impact. Their key results were presented at the CRESCENDO Final Review:

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[65] "CRESCENDO M42 Final Review Meeting", Milestone MS8, Brussels, 23 & 24 October 2012

[66] Whole Integrated Power Plant Coupled Aero-Thermal Model, CRESCENDO test case reference S3P2

[67] See http://www.datadvance.net/

[68] See http://www.plm.automation.siemens.com/en_us/plm/synchronous-technology.shtml

[69] Global Thermal Aircraft Architecture Trade-off, CRESCENDO test case reference S2T1

- "We now have a capability that would allow us to produce a high fidelity whole engine model in the preliminary design timeframe" but as capabilities were developed in parallel "the new automated meshing capability is still to be combined with the parameterisation and optimisation capabilities to deliver further gains". This is the impact of results from the WETMM[70] test case work with USOTON, UBELFAST, UNTUA, CIMNE & TranscenData.
- "We also have capability to perform collaborative robust design at detail component level". This is particularly the impact of the CREDO[71] demonstration achieved by RR-D & RR-UK together with **MTU** and **AVIO** as industrial partners with support from DS, Eurostep, IRIAS, UBRAND, USALENTO & UTORINO as software & research partners.
- "We have demonstrated how to share information in the collaborative environment using engine design outputs as the example surrogate model via web services". This is one impact of the results from the PMPD[72] test case work with AI-F in particular.

The next steps for Rolls-Royce have also been identified, and include: continued development of Simulation Process & Data Management capability and demonstration of CRESCENDO results using the Advanced Simulation Research Centre (ASRC established in Bristol, UK) e.g. for optimisation workflow setup, with software providers (e.g. Siemens & TranscenData) and partners such as Airbus and GKN Aerospace. Rolls-Royce also consider many CRESCENDO results are not yet ready for full deployment and are therefore engaged in further research to reach TRL6 maturity.

The impact for **GKN Aerospace Sweden** (GKNAES, previously Volvo Aero) lies in exploiting the results from the areas of CRESCENDO where they were engaged. The knowledge gained in Value-Driven Design methodologies will be used to develop new business offers, and to further progress the work in a broad direction, GKNAES is also establishing a national research coordination group with Swedish universities and industry. A novel result here was the EVOKE[73] model (Early Value-Oriented design exploration with KnowledgE maturity). In addition, GKNAES intend that the results on multidisciplinary optimisation techniques in preliminary design should be integrated with a set-based approach in collaborative design and analysis. The virtual testing results will be used to establish best practices on the selection of verification methods. Finally, of course, a key expected outcome for GKNAES was to develop the core of the VEC-Hub[74] concept. GKNAES identify six highlights from the Enterprise Collaboration work-package results as a step forward towards a more joined up model-driven collaboration capability.

As a final example of the impact for industry partners, CRESCENDO results contribute widely to the **Snecma** internal technology roadmaps. First in terms of a major impact on collaborative Simulation Process & Data Management capability and architect/integrator environment, although an incomplete exploitation of the BDA Business Object Model is noted from the results of the Product Integration Process[75] demonstration with Airbus, DS, Siemens and Vinci among others. Current engine programs in Snecma are already using the results of the WAVE[76] test case for the specific aspect of water & hail ingestion, delivering improved 3D CFD model calculations. Snecma also sees a significant step forward in managing engineering knowledge with "simulation intent"[77] capture ensuring the quality of meshing to create "fit-for-purpose" analysis models; and future potential for the matching process between simulation data and physical test results

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[70] Whole Engine Thermo-Mechanical Model, CRESCENDO test case reference S2T3

[71] "Collaborative Robust Engine Design Optimisation" within Robust Detailed Design, CRESCENDO test case reference S3P4; also see "Executing optimization processes in the extended enterprise" by R. Parchem (RR-D) & H. Wenzel (DS), submitted for NAFEMS World Congress, Salzburg, 2013

[72] Preliminary Multidisciplinary Power plant Design, CRESCENDO test case reference S2P1

[73] "Value-oriented concept selection in aero-engine sub-systems design: the EVOKE approach" by M. Bertoni & A. Bertoni (ULULEA) with O. Isaksson & H. Amnell (GKNAES), submitted for 23rd Annual INCOSE International Symposium, Philadelphia, USA, 2013; also see Deliverable D2.2.4

[74] Virtual Enterprise Collaboration Hub or VEC-Hub was a key GKNAES result from the previous EU FP6 co-funded VIVACE project

[75] "Innovative Product Integration Process in a collaborative environment" within Thermal & Structural Coupling, CRESCENDO test case reference S3P1

[76] Whole Aero-thermal Virtual Engine, CRESCENDO test case reference S3P5

[77] "Automating analysis modelling through the use of simulation intent", by D. Nolan et al (UBELFAST), submitted for NAFEMS World Congress, Salzburg, 2013

using developed links between PROOSIS[78] and DynaWorks[79]. Snecma will directly exploit 9 of the results identified in the results catalogue (see chapter 4.8 of this report) and has a potential interest in approximately 20 others, but also notes that although the "to-be" processes have been successfully demonstrated in a "research environment", there remains work to be done to validate these internally for use in an "industrial environment".

In addition, it is anticipated that CRESCENDO results will impact other industry initiatives in the near future. One example is with the SAVI (System Architecture Virtual Integration) program[80] within the AVSI (Aerospace Vehicle Systems Institute) hosted by Texas A&M University. A webinar to introduce the CRESCENDO results and follow-on discussions have been held with the SAVI consortium, where current members include Airbus, Boeing, BAE SYSTEMS, Embraer, Rockwell Collins and the US Department of Defence among others. The interest lies in understanding the scope of the BDA Business Object Model and its potential exploitation in relation with the architectural modelling languages and domain models used within SAVI.

4.3 Software vendors impact

The impact for the software vendors community, including PLM and simulation solution providers engaged in the project, was summarised in a keynote address[81] at the CRESCENDO Forum. The opportunity to work closely with aeronautics industry has been crucial for the vendors to gain deeper understanding of the engineering process challenges faced in collaborative product development, and the technical requirements for software to improve the modelling and simulation of the multi-physics behaviour of aircraft. The opportunity to collaborate between the vendors themselves also brings benefits as well as an element of competition. The creation of the Federated Validation Platform during the project (i.e. the industry lab network for the test cases' demonstration scenarios) was a key factor for both these aspects.

The vendors' internal R&D activities and solution roadmaps start to take account of the CRESCENDO results, anticipating richer software tools able to cope with larger and more complex models, as well as interfaces designed for more open collaboration using the BDA Business Object Model.

Finally, the on-going engagement of the software vendors is fundamental in fully realising the objectives of CRESCENDO, through the enhancement of their software solutions and making these available to not only the CRESCENDO consortium but all of their customers including other industry sectors such as automotive, shipbuilding, industrial equipment, and consumer goods.

In the CRESCENDO Forum keynote, the software providers summarised their view of some of the benefits that it is now possible to offer the aeronautical industry:

- "For the first time, Aircraft Architects are able, in a single environment, to carry out trade-offs at any level / any time in the process, while managing collaboration with stakeholders";
- "Holistic simulation of systems to make requirements and design goals visible, enabling more informed early decisions that will result in optimized designs and reduced risk";
- "Short term - the ability to explore more design alternatives with greater confidence; longer term - more certain decision making (lower risk) and effective certification across enterprises".

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[78] "Propulsion Object-Oriented Simulation Software", developed by EAI with support from UNTUA, see http://www.proosis.com/description_proosis.php

[79] DynaWorks software for test data analysis and management, developed by Intespace, see http://www.intespace.net/en/dynaworks-2/intespace-dynaworks.html

[80] See http://savi.avsi.aero/

[81] "Challenges, Responses and Impacts for CRESCENDO solutions and services providers", by H. Karden (Eurostep) et al, at CRESCENDO Forum, Toulouse, June 2012

Indeed, as stated by MSC[82], the software vendors within CRESCENDO "have included collaborative simulation requirements in their development plans in order to steer the ... respective development roadmap to make sure they will fully sustain ... project level dashboard and monitoring (and modelling and simulation) system engineering".

Another indicator is the extent to which the vendors have been active in promoting the CRESCENDO results through their own user community & customer forums, as well as broader industry focussed events. For example, Dassault Systemes invited Airbus[83] [84] to speak about CRESCENDO at the North America and Europe 3DEXPERIENCE customer forums in November 2012, and has also highlighted CRESCENDO on its "perspectives" corporate blog[85] and subsequent webinars. At the 3DEXPERIENCE forums, DS stated how CRESCENDO results are seen as an important step forward, influencing the latest DS "Winning Program" solution offering for Aerospace & Defence. Similar events are planned with MSC Software in 2013. Both DS[86] & MSC[87] have presented their results at the GPDIS (Global Product Data Interoperability Summit) hosted by Boeing & Northrop-Grumman in November 2012, as well as several other events. Siemens PLM software has prepared an overview of their contributions in CRESCENDO for exposure at various webinars in 2013. Siemens will also continue working with Rolls-Royce and Airbus (for example) on CAD geometry processing & coupled analysis, as well as simulation data & process management, as a direct result of their contributions in the thermal and power plant test cases.

The PDT Europe (Product Data Technology) conferences and PLCS Implementers Forum, organised annually by Eurostep, remain another important avenue to raise awareness and engage with both industry and standards communities. Four CRESCENDO results presentations[88] [89] [90] [91] were presented at PDT Europe 2012.

4.4 Future Research Impact

At least two follow-on collaborative research projects plan to exploit and develop results from CRESCENDO.

One is the EU FP7 co-funded TOICA "Thermal Overall Integrated Conception of Aircraft" project due to launch later in 2013. TOICA will re-use and build on key results from CRESCENDO, including Thermal modelling and simulation methods, the BDA Business Object Model and web-services, and the Value-Driven Design methodology in particular. These results will be used to extend the BDA collaboration capabilities; influence the novel "super integration" approach; develop more mature "architects cockpit" implementations; improve the multidisciplinary conception of the global thermal aircraft architecture and radically change the way that thermal studies are performed within aircraft design processes. The fact that 10 out of 32 partners in

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[82] "Illustration of comprehensive Behavioural Digital Aircraft enablement through use cases", by O. Tabaste (MSC) with P. Arbez, S. Grihon, T. Laudan, M. Thomas (AI-F), submitted to the NAFEMS World Congress including 1st international SPDM conference, Salzburg, 2013

[83] "The Behavioural Digital Aircraft vision for simulation in collaborative product development", by P. Coleman (AI-UK), at 3DExperience Forum NA, Orlando, 2012

[84] "Aircraft and Engine manufacturers collaborating to share requirements and converge towards an optimal design", by T. Laudan (AI-F) & V. Tuloup (DS), at 3DExperience Forum NA, Orlando, 2012

[85] "CRESCENDO: tuning up the Behavioural Digital Aircraft", see http://perspectives.3ds.com/industry/crescendo-tuning-up-the-behavioural-digital-aircraft/

[86] "Enabling the Comprehensive Behavioural Digital Aircraft", by M. Macias, S. Khurana, V. Tuloup, H. Wenzel (DS), at GPDIS, Phoenix, 2012

[87] "Being Prepared for the Future: Trade-off Management Technology for Architects within Designing the Robust Virtual Aircraft", by O. Tabaste (MSC) with T. Laudan, S. Grihon, P. Arbez (AI-F), at GPDIS, Phoenix, 2012

[88] "Innovations in collaborative modelling and simulation to deliver the Behavioural Digital Aircraft", by P. Coleman (AI-UK), at PDT Europe, The Hague, 2012

[89] "Developing an Architecture and Standard to Support Innovations in Collaborative Modelling and Simulation", by A. Murton (AI-UK) & N. Shaw (Eurostep), at PDT Europe, The Hague, 2012

[90] "Trade-off management technology for architects within designing the robust virtual aircraft", by O. Tabaste (MSC), at PDT Europe, The Hague, 2012

[91] "Mastering restricted network access in aeronautic collaborative engineering across organisation boundaries with BRICS", by E. Baalbergen (NLR), at PDT Europe, The Hague, 2012

the TOICA consortium were not part of CRESCENDO also indicates some potential impact in terms of knowledge transfer to these organisations.

The other follow-on project is the UK Technology Strategy Board co-funded CONGA "Configuration Optimisation of Next Generation Aircraft" project starting in February 2013. CONGA will also re-use and build on key results from CRESCENDO including the BDA Business Object Model and web-services in particular. These results will be used to develop agile collaboration capabilities and more mature "architects cockpit" implementations; establish interoperability between tools using an OSLC (Open Services for Lifecycle Collaboration) and BDA aligned approach; and influence the novel "Set Based Design" approach to enable the creation of a set of possible product designs comprising different technologies and combinations.

Besides CONGA, Rolls-Royce are also involved in other research to progress CRESCENDO results e.g. "E-BREAK" with whole engine optimisation applied to "real" engine geometry; "Prometheus" with Siemens NX open experience applied to combustor design optimisation; and via the UK co-funded "SILOET" project with integration of maintenance cost & value models in the Rolls-Royce preliminary design system, and possible continuation of large model build & advanced meshing work.

More recently, discussions within EADS have started to assess how the BDA collaboration capabilities could also impact the CRYSTAL (CRitical sYSTem engineering AcceLeration) project that is due to begin in May 2013, co-funded as an ARTEMIS innovation pilot project (AIPP) and follow-on to the previous CESAR[92] (cost-efficient methods and processes for safety relevant embedded systems) project. The underlying goal of CRYSTAL[93] is to accelerate interoperability and reduce system design costs through the improvement and smart integration of system analysis, safety analysis and system exploration tools as well as reduce development cycles with reusable technological bricks.

4.5 Standardisation Strategy Impact

A long-term impact of the CRESCENDO project is the industry-driven standardisation project that is proposed to secure the BDA collaboration standard. This follows the standardisation strategy[94] and recommendations[95] that were established in CRESCENDO.

During the first half of the project, an analysis was performed to assess and select potential applicable standards and approximately 60 standards were identified as relevant to the BDA Architecture. From the analysis, the following standards were identified as particularly relevant: OMG UML and SysML for specification; Web Services Definition Language (WSDL) and related standards for Implementation of communication; ISO 10303-233 (Systems Engineering) and ISO 10303-239 (PLCS) for the underlying information data model and BDA content archive.

In the latter half of the project, the BDA architecture specification was completed and the BDA **Business Object Model** (BOM) was defined as the common language to provide the vocabulary, grammar and syntax for such a collaboration standard. A design approach for information **web services** was also shown to be efficient, re-usable and accessible to implementers.

During CRESCENDO, Eurostep was the only vendor to properly implement a server-side mapping of the BDA Business Object Model with the PLCS-based internal data model of their Share-A-space™ solution. This enabled Share-A-space to act as a collaboration hub and server for the BDA web services within the Federated Validation Platform (FVP described earlier in this report) used to perform many of the industry test cases demonstration scenarios. During the project, other vendors successfully implemented client-side mappings to their proprietary solution data models and were able to send & receive data using BDA Business Objects.

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[92] See http://www.cesarproject.eu/

[93] See http://www.artemis-ia.eu/news/frontpage/news/71

[94] "BDA Standards Strategy and Action Plan", AFNOR et al, Public Deliverable D1.4.5

[95] "BDA Standards recommendations", Eurostep et al, Consortium Confidential Deliverable D5.1.3 and associated Public materials

As the BDA architecture specification will be public, the impact is that any vendor will be able to develop and offer both server- and client-side interoperability capabilities for their proprietary solutions, and be able to demonstrate compliance with the BDA collaboration standard.

In the months since the end of CRESCENDO, an on-going Airbus internal BDA use case focussed on aircraft architecture convergence has allowed MSC and Dassault Systemes to improve the mapping of their proprietary solution data models (i.e. SimManager and ENOVIA respectively) with the BDA Business Object Model in order to also provide BDA server-side collaboration capability.

So the CRESCENDO proposal is to develop a family of **Data EXchange (DEX) specifications** based on the BDA BOM, providing a simplified interpretation of ISO 10303-239/233 as the underlying standards and to enhance the exchange of information and data in the collaborative product development environment envisaged by CRESCENDO. The process is illustrated in Figure 64.

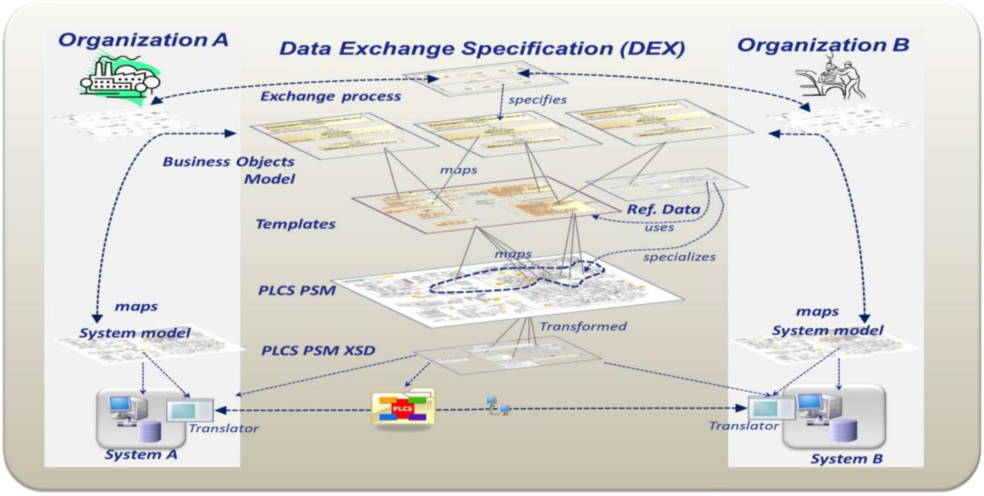
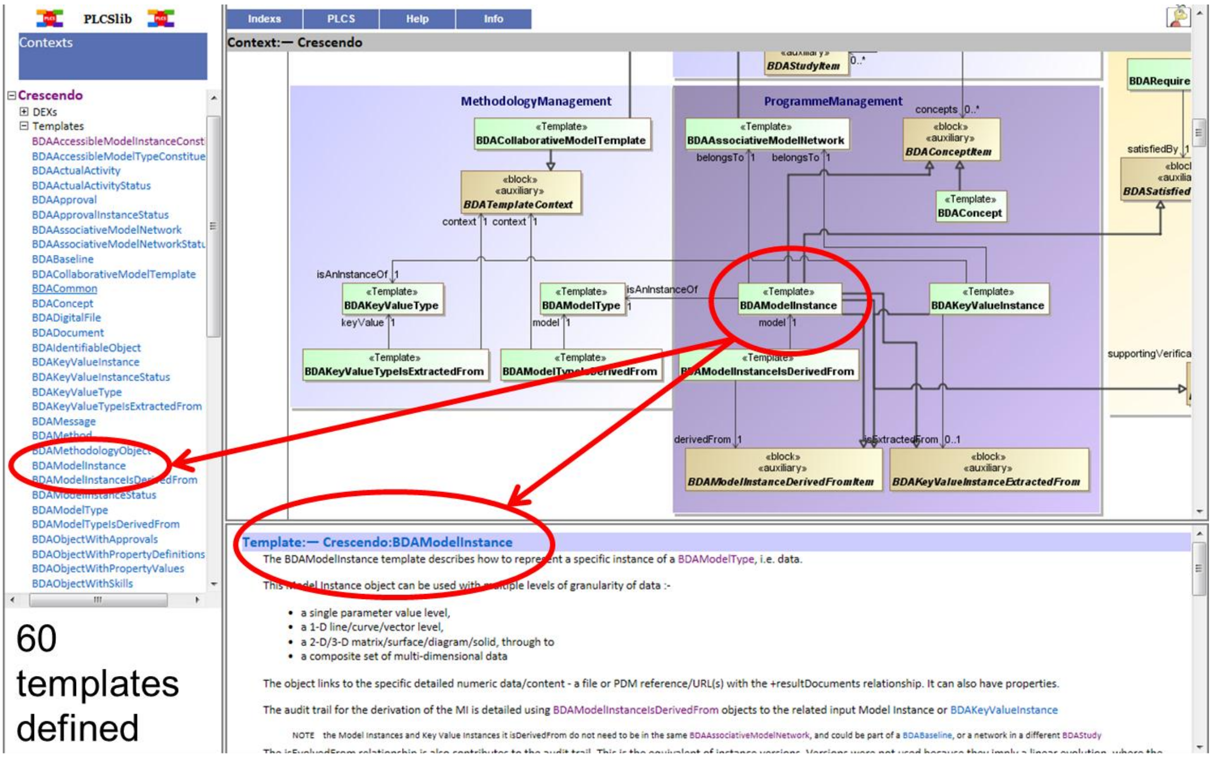


Figure 64: Data Exchange (DEX) Specification



Template:— Crescendo:BDAModelInstance

The BDAModelInstance template describes how to represent a specific instance of a BDAModelType, i.e. data.

This Model Instance object can be used with multiple levels of granularity of data :-

- a single parameter value level,
- a 1-D line/curve/vector level,
- a 2-D/3-D matrix/surface/diagram/solid, through to
- a composite set of multi-dimensional data

The object links to the specific detailed numeric data/content - a file or PDM reference/URL(s) with the +resultDocuments relationship. It can also have properties.

The audit trail for the derivation of the MI is detailed using BDAModelInstanceIsDerivedFrom objects to the related input Model Instance or BDAKeyValueInstance

NOTE the Model Instances and Key Value Instances it isDerivedFrom do not need to be in the same BDAAssociativeModelNetwork, and could be part of a BDABaseline, or a network in a different BDAStudy

Figure 65: BDA Business Object Templates in PLCSlib

Each business object class in the BOM becomes a template in PLCSlib[96] (a SysML based development environment for defining DEXs). So far, there are 60 templates defined, as shown in Figure 65, and two DEX specifications have been built for "AssociativeModelNetworks" and "ModelInstances".

Started in CRESCENDO, the proposal was presented during the 3rd EADS PLM standardisation day in October 2012 and has since gained further support through the EADS-SSC (Strategic Standards Committee) strategy and 5-year roadmap for PLM interoperability standards. In parallel, following an initial webinar in March 2012, the ASD-SSG (AeroSpace & Defence Industries Association of Europe Strategic Standardisation Group) is monitoring the progress of the BDA standardisation activity through its radar chart [97]. A "blip" document (description and adoption statement for each component standard) is being drafted, the standardisation project lead has been established within Airbus and a title for the project has been proposed: "**Modelling and Simulation in collaborative Systems Engineering Context**" (**MoSSEC**). This reflects its wider exploitation potential i.e. not limited to Aerospace & Defence but also for other industry sectors such as Automotive. Following more detailed presentations to ASD-SSG (and also ProSTEP iViP) in March 2013, the short term goals have been agreed, including further communication within Europe and also via PDES Inc. and the US Aerospace Industries Association (AIA). The first "Implementer Forums" are foreseen in 2014.

Another interesting opportunity may arise from an EC sponsored survey, as part of a wider study for CEN and CENELEC (the European standards organisations). This is investigating the extent to which EU-funded research projects have made use of standards or contributed to the development of new standards as part of their activities. CRESCENDO has responded, and may be used by CEN-CENELEC[98] as a case study to highlight the benefits to the wider research community.

4.6 Measuring the progress towards Objectives

A key feature of CRESCENDO was the adoption of Systems Engineering principles[99] in order to guide the overall consistency and coherence of the project activities and results. CRESCENDO followed an iterative approach with three main phases (as shown in Figure 66): Proof-of-Concept, Prototype and Validation. For each phase, specific criteria were agreed[100] to measure progress towards expected completeness and maturity of the results along three key axes of requirements, development and validation:

- The elicitation of requirements (from the end users' viewpoint) and the convergence to acceptance (from the developers' viewpoint) for the "to-be" BDA capabilities.
- The development of the BDA collaboration capabilities and BDA engineering methods, how they are documented in project deliverables, and how they were demonstrated at the key project events (BDA awareness workshop in June 2010, Prototypes Development Workshop in June 2011, and the CRESCENDO Forum in June 2012).
- The validation plans (carried out by the end users' teams in the context of the CRESCENDO test cases) and how they are supported by the functional verification testing (carried out by the methods and capabilities development teams).

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[96] See http://www.plcs.org/plcslib/plcslib/index.html

[97] See http://www.asd-ssg.org/radar-chart

[98] CEN-CENELEC Research & Innovation, see http://www.cencenelec.eu/research/WhyStandards/Pages/default.aspx

[99] "Observations from applying SE principles on a large research project developing Processes, Methods & Tools for Modelling & Simulation of Aircraft Behaviour", by T. Lochow (EADS), T. Laudan (AI-F), S.Sharma & P. Coleman (AI-UK), in Proceedings of the 22nd Annual INCOSE International Symposium, 2012

[100] "CRESCENDO Maturity Review Plan", RR-UK et al, Consortium Confidential Deliverable D1.3.9

Reviews were performed at the end of each project phase[101], with the following assessment versus the targets at the end of the Validation phase:

- Overall requirements completeness & maturity = 100% (versus 100% target).
- Overall development completeness & maturity = 96% (versus 100% target).
- Overall validation completeness & maturity = 80% (versus 100% target).

The validation gap at the end is not seen to be critical and the overall assessment is considered a creditable outcome for such an ambitious research project.

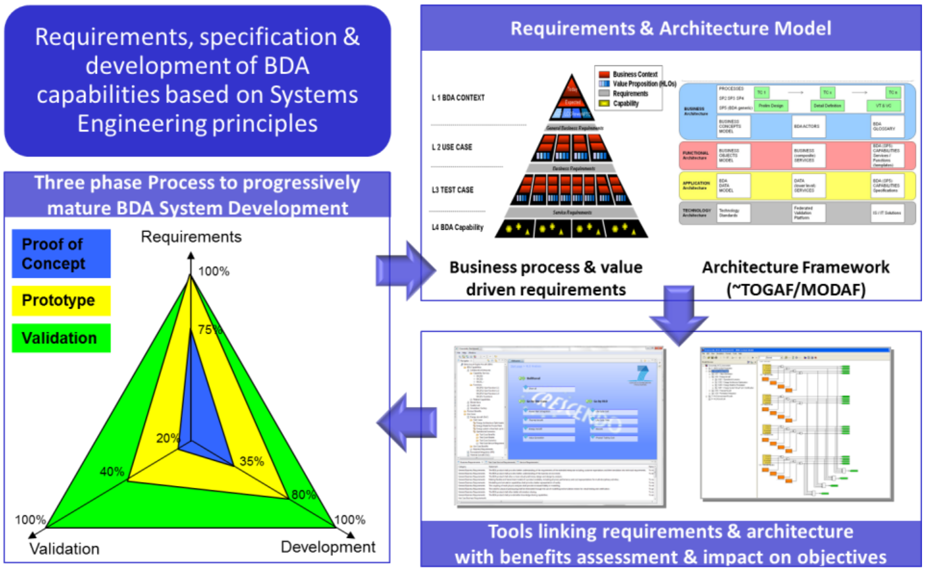

Figure 66: CRESCENDO Systems Engineering approach

An overall benefits assessment methodology was developed and implemented to indicate the impact of the results in terms of High Level Objectives (HLO), considering the specific context of the CRESCENDO test cases[102] and the wider context of potential extension to different aeronautical applications and other industry sectors[103].

The CRESCENDO Systems Engineering Database (**SEDB**) was developed[104] as the means to provide a traceable impact of the results towards the HLO. This was achieved by maintaining the linkage between Test Cases requirements, BDA functions or capabilities, and the benefits assessments; and providing a dashboard viewer accessible to all project participants. All these links were captured using a series of specifically designed project templates. An example screenshot from the SEDB user interface is shown in Figure 67.

The data collected in the CRESCENDO SEDB were used to perform utility value analyses as input to the overall assessment of the **CRESCENDO contribution versus High Level Objectives[105],** as summarised in Table 1. It must be noted that there are some uncertainties in the methodology and the potential improvement can only be considered indicative for the scope of the use cases assessed within CRESCENDO i.e. for the application areas of value generation, thermal aircraft, power plant integration, and virtual testing.

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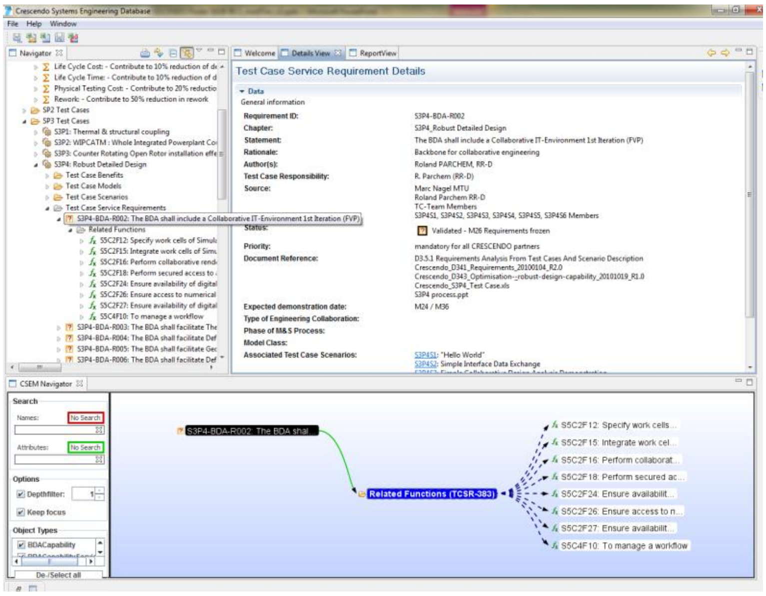
[101] “CRESCENDO Technical Validation Results and Directives”, ALENIA et al, Consortium Confidential Deliverable D1.3.10

[102] “Model demonstrating relationship between results and CRESCENDO High Level Objectives”, EADS et al, Consortium Confidential Deliverable D1.2.1 and Associated Materials

[103] “Benefits perspective from different sectors of the aeronautical industry”, ESOCE et al, Public Deliverable D1.2.5

[104] “Crescendo Systems Engineering database”, EADS et al, Consortium Confidential Deliverable D1.2.2 and Associated Materials

[105] “Assessing the achievement of the High Level Objectives”, RR-UK et al, Consortium Confidential Deliverable D1.2.3



Test Case Service Requirement Details

Data

General information

Requirement ID: S3P4-BDA-R002
Chapter: S3P4_Robust Detailed Design
Statement: The BDA shall include a Collaborative IT-Environment 1st Iteration (FVP)
Rationale: Backbone for collaborative engineering
Author(s): Roland PARCHEM, RR-D
Test Case Responsibility: R. Parchem (RR-D)
Source: Marc Nagel MTU
Roland Parchem RR-D
TC-Team Members
S3P4S1, S3P4S2, S3P4S3, S3P4S4, S3P4S5, S3P4S6 Members
Status: Validated - M26 Requirements frozen
Priority: mandatory for all CRESCENDO partners
Document Reference: D3.5.1 Requirements Analysis From Test Cases And Scenario Description
Crescendo_D341_Requirements_20100104_R2.0
Crescendo_D343_Optimisation-_robust-design-capability_20101019_R1.0
Crescendo_S3P4_Test Case.xls
S3P4 process.ppt
Expected demonstration date: M24 / M36
Type of Engineering Collaboration:
Phase of M&S Process:
Model Class:
Associated Test Case Scenarios: S3P4S1: "Hello World"
S3P4S2: Simple Interface Data Exchange

Figure 67: CRESCENDO Systems Engineering DataBase interface

CRESCENDO High Level Objective	Target HLO reduction for CRESCENDO contribution	Assessment of achievable contribution
Development Life Cycle Cost	10%	5.5% - 9.5%
Development Life Cycle Time	10%	4.4% – 9.2%
Rework	50%	30% – 47%
Physical Testing Costs	20%	16% – 21%

Table 1: Assessment of CRESCENDO contribution versus High Level Objectives

4.7 CRESCENDO project dissemination activities

4.7.1 BDA Prototypes Demonstration Workshop

The emerging business value of the overall BDA approach was demonstrated at the M26 BDA Prototypes Demonstration Workshop (PDW)[106] in June 2011, with approximately 180 participants including all consortium partners, the EC project officer and external reviewers. The M26 PDW was organised in parallel sessions to show the 7 main areas of project results illustrated previously in Figure 6. A complete list of the 50 presentations and the partners involved is included in the Appendix B (Table 4 and Table 5) of this Final Report and will be published on the public website. There was positive feedback on the outcomes from the M26 PDW including from the Airbus mechanical systems integration architect, who commented that “Collaborative Engineering in a multi-disciplinary context is clearly the foundation of next generation aircraft architecture; architects have to mix physical, functional, operational views to build the complete assessment; and the solutions proposed are compliant with the Architect’s strategy and have to be considered”.

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[106] “Internal dissemination event (M26 Prototype Development Workshop)”, Milestone MS5, Toulouse, 15-17 June 2012, and related Consortium Confidential Deliverable D0.2.3

Figure 68: Photographs from the CRESCENDO Forum & Marketplace

4.7.2 CRESCENDO Forum and Industry supply chain dissemination events

One of the most significant events of the project, the M38 CRESCENDO Forum[107] was held over three days in June 2012, at the Météo-France International Conference Centre in Toulouse. This public dissemination event, attended by over 320 participants including 12 non-consortium organisations, was the occasion to share the results of the project and demonstrate the achievements to the main stakeholders i.e. the Consortium partners and European Commission. Some photographs from the event are shown in Figure 68. The **Forum Handbook** (154 pages)[108] produced to introduce the CRESCENDO results and provide a guide to the event, together with the 82 posters used at the event, were distributed electronically to all participants and will also be published on the public website. A complete list of the 45 technical results presentations and partners involved (Table 6, Table 7, Table 8) and a map of the 30 marketplace stands (Table 9) are provided in Appendix B of this Final Report.

To further disseminate the results, four additional **industry and supply chain events** were held during September & October 2012, with the Hamburg Aviation cluster, Toulouse Aerospace Valley and GIFAS, UK Royal Aeronautical Society (Bristol branch) and UK Aerospace, Aviation and Defence Knowledge Transfer Network (AAD-KTN). AI-UK, AI-F, RR-UK, EADS, MSC, DS and CERFACS were responsible for organising and running these three face-to-face meetings and the AAD-KTN webinar.

4.7.3 Wider Dissemination of CRESCENDO results

During the project, CRESCENDO presented results at two specific EC sponsored events. The first major public communication of CRESCENDO project objectives and progress was delivered by the coordinator[109] at the **Aerodays 2011**, organised by the EC. Another overview of the project and specific insight into the Virtual Testing methodology and related test cases' results[110] was presented by AI-UK, ECPTR and SNECMA at a specific workshop on virtual testing also including other EU projects from automotive, maritime and rail sectors.

Together with these events and publications already referenced previously in this report, at least **75 papers or presentations for scientific journals, international conferences or other seminars** worldwide were produced by CRESCENDO within the project duration. In addition, **6 university theses** linked with the CRESCENDO results have been published. Between the end of the project and April 2013, at least **20 more publications** have been prepared.

All these dissemination activities are detailed in a separate part of this Final Report. However, it is interesting to note that at least four publications[111] [112] [113] [114] received "best paper" awards at their respective conferences.

All CRESCENDO related public dissemination activities are subject to advance approval by CRESCENDO Steering Committee vote, to avoid any IPR issues. According to the internal consortium rules, Steering Committee approval will continue to be sought by partners for the duration of two years after the project end (i.e. until 31/10/2014).

It is also anticipated that CRESCENDO results will become more widely known and influence the activities of INCOSE[115] and NAFEMS[116] working groups.

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[107] "M38 CRESCENDO Forum", Milestone MS7, Toulouse, 19-21 June 2012, and related Public part of Deliverable D0.2.4

[108] "CRESCENDO Forum Handbook Final USB.pdf" as Public part of related "CRESCENDO Forum Proceedings" Deliverable D0.2.5

[109] "Developing the BDA", by P. Coleman (AI-UK), at 6th European Aeronautics Days, Madrid, 2011; see http://www.cdti.es/recursos/doc/eventosCDTI/Aerodays2011/3D1.pdf

[110] "CRESCENDO project overview and focus on VIRTUAL TESTING", by P. Coleman (AI-UK), R. Marhic (ECPTR) & F. Beley (SNECMA), at EC Transport cross sector fertilisation workshop on virtual testing, Brussels, 2012

[111] "Communicating the Value of PSS Design Alternatives Using Color-Coded CAD Models", by A. Bertoni, M. Bertoni (ULUEA) and O. Isaksson (VOLVO), in Proceedings of the 3rd CIRP International Conference on Industrial Product Service Systems, 2011

[112] "A framework to report and to analyse a debate", by T. Polacsek & L. Cholvy (ONERA), in Proceedings of the 15th International Conference on Computer Supported Cooperative Work in Design, 2011

[113] "Automatic Decomposition and Efficient Semi-structured Meshing of Complex Solids", by J. Makem, C. Armstrong & T. Robinson (UBELFAST), in Proceedings of the 20th International Meshing Roundtable, 2011

[114] "Understanding Airlines Value Perceptions For Value-Based Requirements Engineering of Commercial Aircraft", by X. Zhang, G. Auriol, C. Baron (UINSAT), H. Eres (USOTON) & M. Kossmann (AI-UK), in Proceedings of the 22nd Annual INCOSE International Symposium, 2012

The NAFEMS community already has some awareness, through various events where CRESCENDO results have been disseminated, including MSC[117] at NAFEMS congresses in 2011 & 2012, and Airbus[118], MSC[119], DS & EADS[120] at "Les défis du SDM" seminar in 2012. A further six CRESCENDO related papers are expected at the NAFEMS World Congress & SPDM conference in 2013. LMS[121] have also promoted their work within a NAFEMS MBSE workshop.

GKNAES and EADS are actively pursuing opportunities to promote the CRESCENDO Value-driven Design (VDD) methodology results within INCOSE, potentially through interaction with the Model-Based Systems Engineering (MBSE) working groups. To some extent, this follows the successful dissemination activity at the INCOSE International Symposium in 2012 (where four CRESCENDO related papers were presented) and further meetings are planned at the 2013 Symposium in June (where two further papers on VDD and the EVOKE approach will be presented).

Another opportunity is with the new joint cross-organisational working group on Systems Modelling and Simulation (SMS-WG)[122] announced by NAFEMS and INCOSE in 2012. The vision of the SMS-WG has clear similarities with the ambition of the CRESCENDO consortium, in terms of "promoting collaboration among multiple engineering disciplines, integrating complex systems engineering processes, and enabling the sharing of intellectual property among globally dispersed teams". The mission of the SMS-WG is to develop a vendor-neutral, end-user driven consortium, advance the technology and best practices of systems engineering and engineering analysis, and support international standards in these areas. Both EADS and Airbus are in a position to influence the activities of this working group and promote the CRESCENDO results to the wider community.

4.8 Preparing the Results for Exploitation beyond CRESCENDO

4.8.1 BDA training and e-Learning Portal

The purpose of the CRESCENDO training is to facilitate deployment and exploitation of the results. The overall approach and example course materials were presented at the CRESCENDO Forum in specific training sessions[123]. The chosen means to access the courses is via the **BDA e-learning portal**[124]. This is based on Moodle: a web-based, open-source Learning Management System (LMS) very popular with universities and company training departments. The content[125] includes the training materials, deployment guidelines, and wiki glossary developed by the partners. As shown in Figure 69, this presents a catalogue of e-learning presentation material and videos (based on CRESCENDO deliverables, PDW and Forum demonstrations) and is structured to introduce the BDA concepts; Methodologies (Value Generation and Virtual Testing); BDA modelling & simulation capabilities; BDA collaboration capabilities; and also the SEDB to illustrate how CRESCENDO developed the results.

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[115] International Council on Systems Engineering (INCOSE) is a not-for-profit membership organisation founded in 1990, see http://www.incose.org/

[116] NAFEMS is the International Association for the Engineering Modelling, Analysis and Simulation Community, a not-for-profit organisation established in 1983, see http://www.nafems.org/

[117] "Behavioural Digital Aircraft & Virtual Certification", O. Tabaste (MSC), at NAFEMS World Congress, Boston, USA, 2011

[118] "Crescendo – Enjeux, retours d'expérience, solutions, projection", by T. Chevalier (AI-SAS), at NAFEMS Les défis du SDM, Paris, 2012

[119] "Developing the Thermal AC along Life Cycle", by O. Tabaste (MSC) with P. Arbez & M. Thomas (AI-F), at NAFEMS Les défis du SDM, Paris, 2012

120 "Crescendo use case : Avion numérique comportemental, application aux dissipations thermiques", by O. Hardy (DS) & Y. Baudier (EADS), at NAFEMS Les défis du SDM, Paris, 2012

[121] "CRESCENDO Final Review: Work performed by LMS", by V. Braibant & L. Allain (LMS), at NAFEMS workshop on Model-Based System Engineering, December 2012

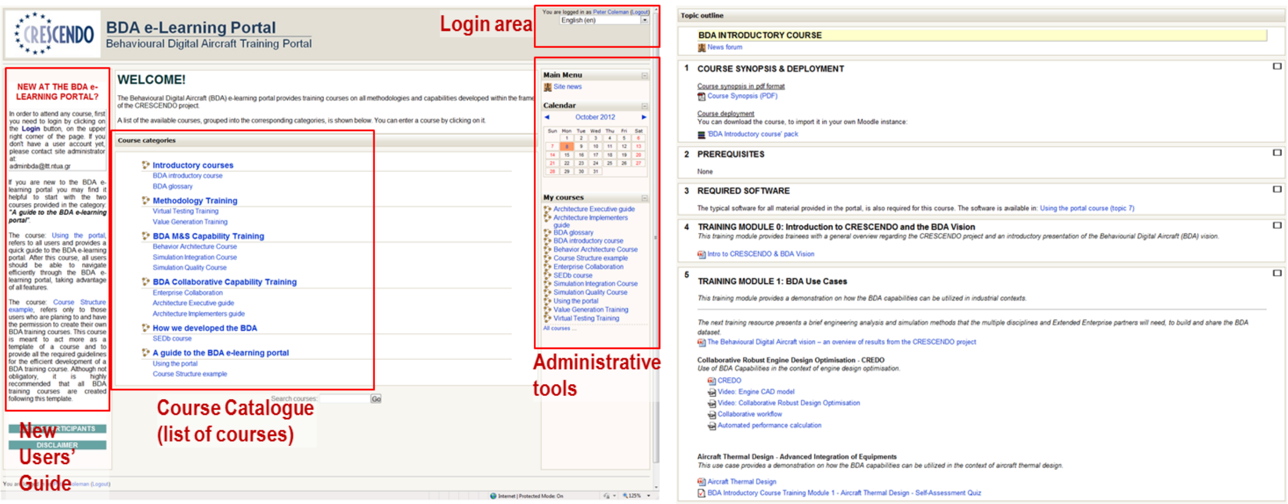
[122] See http://www.nafems.org/media/news/latest1007/nafems_announces_collaboration_with_incose/ or http://www.incose.org/newsevents/news/details.aspx?id=266

[123] "Impact of BDA Training Session Reports", UNINOVA et al, Consortium Confidential Deliverable D1.5.3

[124] "BDA On-line training Portal providing access to training material and project results", UNTUA et al, Consortium Confidential Deliverable D1.5.4

[125] "BDA targeted training programmes and associated training materials", ULULEA et al, Public Deliverable D1.5.2

Considerable effort was placed in the final months of CRESCENDO to gather feedback and refine the content of the BDA e-Learning portal to provide a legacy at the project end. It was agreed[126] that the National Technical University of Athens (UNTUA) will continue to maintain the BDA e-Learning portal for a period of 3 years (up to October 2015) but the access and content currently remains consortium confidential.



NEW AT THE BDA e-LEARNING PORTAL?

In order to attend any course, first you need to login by clicking on the **Login** button, on the upper right corner of the page. If you don't have a user account yet, please contact site administrator at: adminbda@ltt.ntua.gr

If you are new to the BDA e-learning portal you may find it helpful to start with the two courses provided in the category: *"A guide to the BDA e-learning portal"*.

The course: Using the portal, refers to all users and provides a quick guide to the BDA e-learning portal. After this course, all users should be able to navigate efficiently through the BDA e-learning portal, taking advantage of all features.

The course: Course Structure example, refers only to those users who are planing to and have the permission to create their own BDA training courses. This course is meant to act more as a template of a course and to provide all the required guidelines for the efficient development of a BDA training course. Although not obligatory, it is highly recommended that all BDA training courses are created following this template.

WELCOME!

The Behavioural Digital Aircraft (BDA) e-learning portal provides training courses on all methodologies and capabilities developed within the frame of the CRESCENDO project.

A list of the available courses, grouped into the corresponding categories, is shown below. You can enter a course by clicking on it.

Course categories

- **Introductory courses**
  - BDA introductory course
  - BDA glossary
- **Methodology Training**
  - Virtual Testing Training
  - Value Generation Training
- **BDA M&S Capability Training**
  - Behavior Architecture Course
  - Simulation Integration Course
  - Simulation Quality Course
- **BDA Collaborative Capability Training**
  - Enterprise Collaboration
  - Architecture Executive guide
  - Architecture Implementers guide
- **How we developed the BDA**
  - SEDb course
- **A guide to the BDA e-learning portal**
  - Using the portal
  - Course Structure example

BDA INTRODUCTORY COURSE

1 **COURSE SYNOPSIS & DEPLOYMENT**

Course synopsis in pdf format
Course Synopsis (PDF)

Course deployment
You can download the course, to import it in your own Moodle instance:
'BDA Introductory course' pack

2 **PREREQUISITES**

None

3 **REQUIRED SOFTWARE**

The typical software for all material provided in the portal, is also required for this course. The software is available in: Using the portal course (topic 7)

4 **TRAINING MODULE 0: Introduction to CRESCENDO and the BDA Vision**

This training module provides trainees with a general overview regarding the CRESCENDO project and an introductory presentation of the Behavioural Digital Aircraft (BDA) vision.

Intro to CRESCENDO & BDA Vision

5 **TRAINING MODULE 1: BDA Use Cases**

This training module provides a demonstration on how the BDA capabilities can be utilized in industrial contexts.

The next training resource presents a brief engineering analysis and simulation methods that the multiple disciplines and Extended Enterprise partners will need, to build and share the BDA dataset.

The Behavioural Digital Aircraft vision – an overview of results from the CRESCENDO project

Collaborative Robust Engine Design Optimisation - CREDO
Use of BDA Capabilities in the context of engine design optimisation.
- CREDO
- Video: Engine CAD model
- Video: Collaborative Robust Design Optimisation
- Collaborative workflow
- Automated performance calculation

Aircraft Thermal Design - Advanced Integration of Equipments
This use case provides a demonstration on how the BDA capabilities can be utilized in the context of aircraft thermal design.
- Aircraft Thermal Design
- BDA Introductory Course Training Module 1 - Aircraft Thermal Design - Self-Assessment Quiz

(a) BDA e-Learn Portal Home Page (b) Extract from BDA Introductory Course Modules

Figure 69: BDA e-Learning portal (http://elearn.ltt.ntua.gr/)

4.8.2 The Results Catalogue and Guidelines for exploitation beyond CRESCENDO

Another achievement from the validation phase, and part of the legacy of the project, is the compilation of a **CRESCENDO Results Catalogue**[127]. The purpose is to provide a peer reviewed assessment of the maturity of the results and their readiness for exploitation.

The public version will be available on the public website and comprises a user guide document, excel spreadsheet, and complementary illustrated handbook providing contacts as well as short descriptions and maturity assessments, for over **80 exploitable results** from the project.

An excel template was used to establish a common structure to describe results by the result owners and developers, and some guidelines were developed to help partners to fill in the different types of information required. The template comprises three parts:

- Basic CRESCENDO result information e.g. Id, title, description, owner(s), contacts, advances through CRESCENDO, significance.
- CRESCENDO result maturity e.g. evaluated level, justification, evidence, other results needed, other reference documents.
- CRESCENDO result items e.g. type of result and format.

In CRESCENDO, it was decided not to attempt a full TRL (Technology Readiness Level) assessment of individual results, as this will be performed by impacted partners according to their own procedures, but to use three simpler maturity levels for an indicative assessment:

- **Successful proof-of-concept**: Level at which active R&D is initiated and scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data.
- **Validated in experimental lab**: Level at which basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency

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[126] "BDA Training Policy for the training system and related training material", EADS et al , Deliverable D1.5.1

[127] "CRESCENDO Results catalogue", ECPTR et al, Public Deliverable D0.3.1

and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, and scalability issues. Emulation is with current/legacy elements as appropriate. Prototypes are developed to demonstrate different aspects of the eventual system.

- **Validated in Industrial Lab**: Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment / interfaces. Experiments are done with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment.

For reference, an extract from the Results Catalogue excel spreadsheet is included in Appendix C of this Final Report. Table 10 and Table 11 list the results according to a classification that was proposed to simplify the exploitation by partners and provides a primary index to the Catalogue. This classification is consistent with the categories also used for the BDA e-learning portal, and tends to illustrate the CRESCENDO and BDA results in terms of:

- BDA collaboration capabilities (e.g. results linked with collaboration and data management);
- BDA modelling and simulation capabilities (e.g. BDA behaviour architect capabilities, BDA simulation integration capabilities and BDA simulation quality capabilities; also linked with BDA engineering methods such as mesh-based process organisation, architecture trade-offs, system-level representations, multi-physics coupling, confidence in simulation quality);
- BDA methodologies (e.g. Value Generation and Virtual Testing methodologies);
- Training material and project management tools and methodology;
- Standardisation.

Two further public deliverable documents provide general guidelines to support the exploitation of the results beyond CRESCENDO.

One deliverable[128] provides a general evaluation of both advantages (benefits) and potential disadvantages (costs) that may be anticipated as a consequence of the innovations demonstrated during CRESCENDO. The approach is taken from the perspective of different classes of companies in the aeronautical industry, as shown in Figure 70.

Another deliverable[129] intends to provide business decision makers in the aeronautical supply chain with information supporting and guiding their choices for taking up the project's results. It asserts that it is necessary to be realistic about the levels of effort and timescales required to implement the innovative results from the CRESCENDO project and the general assumption is that the exploitation strategy and planning depend on two main aspects:

- An evaluation and understanding of benefits and disadvantages to an enterprise's internal business environment and on its interfacing entities, i.e. customers, partners and suppliers;
- An assessment of available exploitable results and their related maturity, so as to properly identify the enterprise-specific actions (further research and technological development) necessary for successful industrial use.

Using the results catalogue as the reference, the consortium beneficiaries were surveyed to declare their interest in the results: first as one of the owners or developers of each result; and second as potential exploiter of each result over the next few years.

In this way, common interests can be derived in terms of the results exploitation potential. Although this is a very subjective method, and should be treated with caution, Table 2 indicates the most popular results for exploitation by the consortium at the end of October 2012. All these results have been highlighted in chapter 3 of this report.

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[128] "Benefits perspective from different sectors of the aeronautical industry", ESOCE et al, Public Deliverable D1.2.5

[129] "Results Exploitation beyond CRESCENDO", ESOCE et al, Public Deliverable D0.3.3

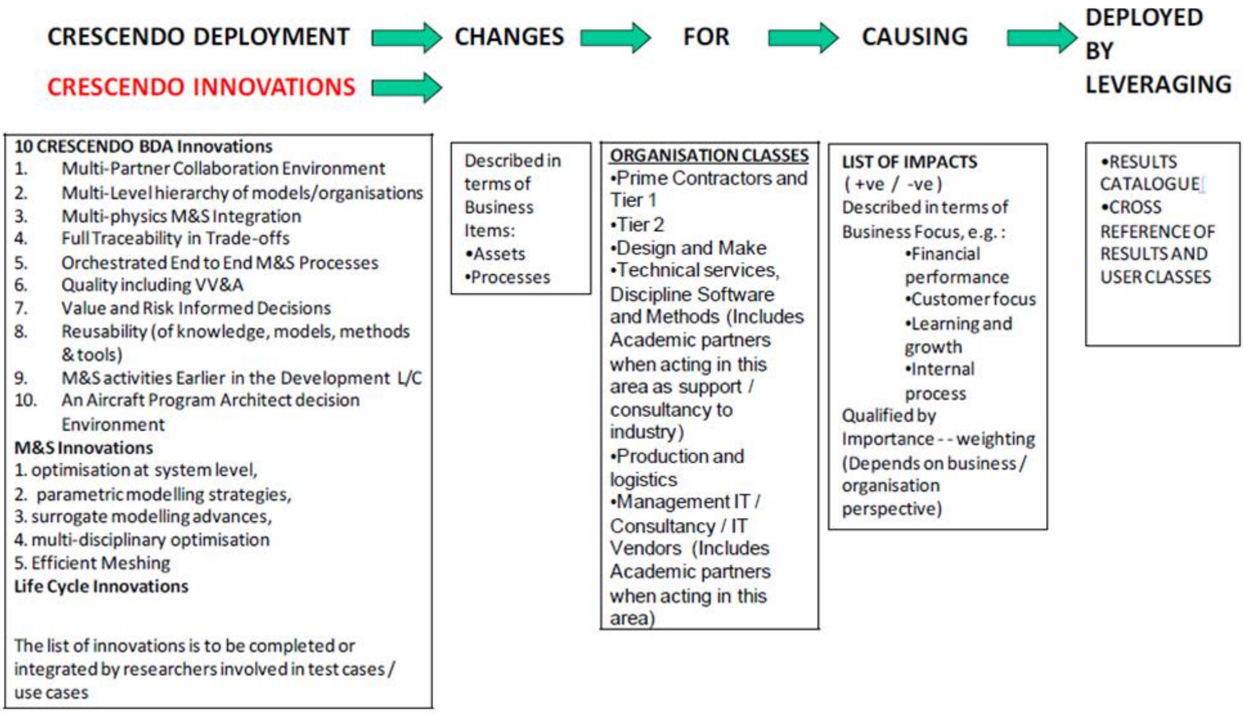

Figure 70: Guidelines for assessing impact of results in different classes of industry

Result Id	Result Title	Number of partners with a declared interest in exploiting the result
R102	BDA Architecture - Business Object Model	21
R53	Behaviour Architect Capability	18
R54	BDA Credibility Assessment Scale (CAS) dashboard with quality indicators	15
R29	Automated efficient meshing	15
R40	Specification of Behaviour Architect role	14
R103	BDA Data Services - Web Service Definition and Services	14
R86	Numerical methods for the modelling and propagation of uncertainty	14
R52	Behavioural Digital Aircraft Capabilities Enabling Secure Collaboration	13
R7	Value-driven Design Methods in Engineering Optimisation - Comparing Design Strategies	13
R98	Generic process for Virtual Testing & Virtual Certification	13
R63	Efficient geometry cleaning process	13

Table 2: Assessment of the most popular results for exploitation by the CRESCENDO consortium

Appendix A - CRESCENDO project beneficiaries and contact details

Where appropriate, scientific/technical contact names are provided in the table below, rather than financial/administrative contacts, although more than one contact name is provided for some beneficiaries.

#	Short Name	Beneficiary Name	Country	Contact Name	Contact email
1	AI-UK	Airbus Operations Limited (COORDINATOR)	UK	Peter COLEMAN	peter.coleman@airbus.com
2	AFNOR	Association Française de Normalisation	France	Nicolas SCUTO	nicolas.scuto@afnor.org
3	AI-D	Airbus Operations GmbH	Germany	Tim GIESE	tim.giese@airbus.com
4	AI-F	Airbus Operations SAS	France	Jean-Claude DUNYACH	jean-claude.dunyach@airbus.com
5	AI-SAS	Airbus SAS	France	Pascal GENDRE	pascal.gendre@airbus.com
6	AIRCELLE	Aircelle SA	France	Colette De le Fouchardière	colette.delafouchardiere@aircelle.com
7	ALENIA	Alenia Aermacchi SPA	Italy	Pierpaolo BORRELLI	pborrelli@alenia.it
8	ALTRAN	ALTRAN Technologies S.A.	France	Sebastien ROUVREAU	sebastien.rouvreau@altran.com
				Jean-Marc PUEL	jean-marc.puel@altran.com
10	ARTTIC	ARTTIC SAS	France	Hugo HART	hart@arttic.eu
11	ESOCE	Associazione ESOCE Net European Society of Concurrent Engineering Net	Italy	Bruno LISANTI	bruno.lisanti@esoce.net
12	AVIO	Avio S.p.A.	Italy	Roberto MEROTTO	roberto.merotto@aviogroup.com
13	UBRAND	Brandenburgische Technische Universitat Cottbus	Germany	Dieter BESTLE	bestle@tu-cottbus.de
14	CERFACS	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	France	Jean-Christophe JOUHAD	jjouhaud@cerfacs.fr
15	CIMNE	Centre Internacional de Mètodes Numèrics en Enginyeria	Spain	Gabriel BUGEDA	bugeda@cimne.upc.edu
16	UCRAN	Cranfield University	UK	Marin GUENOV	M.D.Guenov@Cranfield.ac.uk
17	DS	Dassault Systèmes SA	France	Vincent TULOUP	vincent.tuloup@3ds.com

#	Short Name	Beneficiary Name	Country	Contact Name	Contact email
18	DLR	Deutsches Zentrum fuer Luft - und Raumfahrt eV	Germany	Johann BALS	Johann.Bals@dlr.de
				Klaus SCHNEPPER	Klaus.Schnepper@dlr.de
19	EAI	Empresarios Agrupados Internacional SA	Spain	Pedro COBAS	pce@ecosimpro.com
20	ECPTR	Eurocopter SAS	France	Ronan MARHIC	ronan.marhic@eurocopter.com
22	EUROSTEP	Eurostep AB	Sweden	Hakan KARDEN	hakan.karden@eurostep.com
			UK	Nigel SHAW	nigel.shaw@eurostep.com
23	FLUOREM	Fluorem	France	Macoumba N'DIAYE	macoumba.ndiaye@fluorem.com
				Laurent DELMAS	laurent.delmas@fluorem.com
24	FFT	Free Field Technologies SA	Belgium	Jean-Louis MIGEOT	jean-louis.migeot@fft.be
25	FUJITSU	Fujitsu Systems Europe	UK	Ian GODFREY	ian.godfrey@fr.fujitsu.com
26	UINSAT	Institut National des Sciences Appliquées de Toulouse INSAT	France	Claude BARON	claude.baron@insa-toulouse.fr
27	IRIAS	International Research Institute for Advanced Systems	Russia	Irina EFIMOVA	i.efimova@irias.ru
				Sergey MOROZOV	sergey.morozov@datadvance.net
28	ISPACE	INTESPACE	France	Joseph MERLET	joseph.merlet@intespace.fr
29	ENGS	iSIGHT Software EURL	France	Olivier HARDY	olivier.hardy@3ds.com
			Germany	Holger WENZEL	Holger.WENZEL@3ds.com
30	IAI	Israel Aerospace Industries Ltd.	Israel	Arie SMOLANSKY	asmolan@iai.co.il
31	ULINK	Linköpings Universitet	Sweden	Johan OLVANDER	Johan.olvander@liu.se
33	ULULEA	Lulea Tekniska Universitet	Sweden	Christian JOHANSSON	christian.johansson@ltu.se
34	MSC	MSC Software GmBH	Germany	Olivier TABASTE	olivier.tabaste@mscsoftware.com
35	MTU	MTU Aero Engines GmbH	Germany	Marc NAGEL	marc.nagel@mtu.de
36	UNTUA	National Technical University of Athens	Greece	Kostas MATHIOUDAKIS	kmathiou@central.ntua.gr

#	Short Name	Beneficiary Name	Country	Contact Name	Contact email
				Alexiou ALEXIOS	a.alexiou@ltt.ntua.gr
37	ONERA	Office National d'Etudes et de Recherches Aerospatiales	France	Christophe BLONDEAU	Christophe.Blondeau@onera.fr
				Sylvain MOUTON	sylvain.mouton@onera.fr
				Thomas POLACSEK	thomas.polacsek@onera.fr
				Brigitte GIACOMI	brigitte.giacomi@onera.fr
38	PARAGON	Paragon Anonymh Etaireia Meleton Erevnas Kai Emporiou Proigmenhs Texnologias	Greece	Jason TSAHALIS	jtsahalis@paragon.gr
39	UTORINO	Politecnico di Torino	Italy	Paolo MAGGIORE	paolo.maggiore@polito.it
40	PYRAMIS	Pyramis	France	Michel AUNEAU	michel.auneau@pyramis-online.com
				Patrick LANGLADE	patrick.langlade@pyramis-online.com
41	UBELFAST	Queen's University Belfast	UK	Cecil ARMSTRONG	c.armstrong@qub.ac.uk
42	RR-D	Rolls-Royce Deutschland Ltd & Co KG	Germany	Roland PARCHEM	roland.parchem@rolls-royce.com
43	RR-UK	Rolls Royce Plc	UK	Paul WEBSTER	paul.webster@rolls-royce.com
				Andrew ROLT	Andrew.rolt@rolls-royce.com
44	SAAB	SAAB Aktiebolag	Sweden	Christina ALTKVIST	Christina.Altkvist@saabgroup.com
45	SAMTECH	SAMTECH SA	Belgium	Claudine BON	claudine.bon@samtech.com
				Alain REMOUCHAMPS	alain.remouchamps@samtech.com
46	USALENTO	Università del Salento	Italy	Angelo CORALLO	angelo.corallo@ebms.unile.it
47	SHORTS	Short Brothers Plc	UK	John BELSHAW	john.belshaw@aero.bombardier.com
				David RIORDAN	david.riordan@aero.bombardier.com
48	SIEMENS	Siemens Industry Software SAS	France	Gilles DUBOURG	gilles.dubourg@siemens.com
49	SNECMA	Snecma SA	France	Thomas NGUYEN VAN	thomas.nguyenvan@snecma.fr
50	USOTON	University of Southampton	UK	James SCANLAN	J.P.Scanlan@soton.ac.uk
				Andy KEANE	Andy.Keane@soton.ac.uk

#	Short Name	Beneficiary Name	Country	Contact Name	Contact email
51	NLR	Stichting Nationaal Lucht- en Ruimtevaarrtlaboratorium	Netherlands	Johan KOS	kos@nlr.nl
52	THALES	Thales Avionics SA	France	Marc FABREGUETTES	marc-g.fabreguettes@fr.thalesgroup.com
				Claude SARNO	claude.sarno@fr.thalesgroup.com
53	TRN	TranscenData Europe Limited	UK	Henry BUCKLOW	henry.bucklow@transcendata.com
				Geoffrey BUTLIN	geoffrey.butlin@transcendata.com
54	TM	Turbomeca SA	France	Emilie BASSET	emilie.basset@turbomeca.fr
				Bernard PONS	bernard.pons@turbomeca.fr
55	UNINOVA	UNINOVA - Instituto de Desenvolvimento de Novas Tecnologias	Portugal	Ricardo GONCALVES	rg@uninova.pt
56	UCAM	The Chancellor, Masters and Scholars of the University of Cambridge	UK	John CLARKSON	pjc10@eng.cam.ac.uk
57	ULIM	University of Limerick	Ireland	David NEWPORT	david.newport@ul.ie
58	VINCI	Vinci Consulting	France	Michel MAURINO	michel.maurino@vinci-consulting.com
59	GKNAES	GKN Aerospace Sweden AB	Sweden	Mats LINDEBLAD	Mats.Lindeblad@gknaerospace.com
				Ola ISAKSSON	ola.isaksson@gknaerospace.com
60	LMS	LMS Imagine SA	France	Loig ALLAIN	loig.allain@lmsintl.com
61	EADS	European Aeronautic Defence and Space Company EADS FRANCE SAS	France	Yves BAUDIER	yves.baudier@eads.net
62	ANSYS	ANSYS France SAS	France	Stéphane PERRIN	Stephane.Perrin@ansys.com

Table 3: CRESCENDO project beneficiaries and contact details

Appendix B – M26 PDW and M38 Forum presentations

M26 Prototypes Demonstration Workshop presentations

PDW ref	**Results Session**	**Results Presentation / Demonstration**	**Organisations Involved**
1	Introduction	Workshop Objectives and overview of CRESCENDO results	AI-UK, VOLVO, AI-F, SNECMA, ECPTR, NLR
3.3.1	Value Generation concept and capability demos	Introduction to the Value Generation Concept	VOLVO
3.3.2		The Value Creation Strategy	EADS, AI-UK, UINSAT, PYRAMIS
3.3.3		Improving concept down selection by simulating surplus value for a fleet of aircraft	RR-UK, USOTON
3.3.4		Value Vizualization and decision support	ULULEA, VOLVO
2.2.1	Thermal Aircraft use case demos	Global Thermal Aircraft Overall Design	AI-F
2.2.2		Architecture and system-level thermal behavioural representation of the Aircraft	AI-F, EADS, DS, LMS
3.2.1		Developing the Thermal Aircraft along different life-cycle phases and engaging the Extended Enterprise	AI-F, MSC, ALENIA, IAI, EUROSTEP
3.2.2		An Architect Dashboard : Supporting the Overall Aircraft Design and Validation	AI-F, MSC, EADS
4.2.1		APU Compartment Thermal Modelling (S2T1 s4).	IAI, AI-F
4.2.2		Change Propagation in Workflows (CPiW)	AI-F, UCAM
4.2.3		Numerical thermal analysis for equipment qualification tests - Climatic Virtual Testing (S4T1 s4)	ISPACE, THALES
4.2.4		Cabin Layout optimization (S2T1) and Chemical Oxygen Generator Activation Simulation (S3T1)	ALENIA, USALENTO, UTORINO
2.1	Powerplant Integration use case demos	Preliminary Multidisciplinary Powerplant Design	AI-F, NLR, SAMTECH, ENGS, UCRAN, UBRAND, UBELFAST, USOTON
3.1.1		Whole Engine Thermo-Mechnical Optimisation in Preliminary Design (S2T3)	CIMNE, RR-UK, UBELFAST, USOTON
3.1.2		Detailed design optimisation in a collaborative environment	RR-D, RR-UK, MTU, UBRAND, IRIAS, USOTON, DS, SIEMENS
4.1.1		Innovative Product Integration process in a collaborative environment for detailed design	AI-F, AI-D, ALTRAN, SHORTS, SNECMA,DS, CIMNE, SIEMENS, VINCI
4.1.2		Distributed modelling for power plant thermal integration	AI-F, AIRCELLE, ECPTR, SHORTS, SNECMA, TM, IRIAS, FUJITSU
4.3.1		Introducing Virtual Testing for Fire Protection Certification	AVIO, INTESPACE, USALENTO
4.3.2		Matching process between simulation data and physical test results - Performances	SNECMA, INTESPACE, EAI
4.3.3		Matching process between simulation data and physical test results - Nacelle anti-icing	SHORTS, DS
4.3.4		Advances in aero-acoustic modelling and simulation	AI-F, CERFACS, ONERA, SNECMA, FFT
6.3.1	Energy System Virtual Test demos	Energy System VT : Introduction to Challenges and Test Case scope	EADS, SAAB
6.3.2		Reducing physical tests through uncertainty analysis via integrated models (S4E1 s12)	SAAB, EADS, AI-D, ULINK, DS
6.3.3		Demonstration of electrical system fault detection tool principles and operation for measurement data	PARAGON

Table 4: M26 PDW results presentations / demonstrations (part 1)

PDW ref	Results Session	Results Presentation / Demonstration	Organisations Involved
5.1.1	BDA Collaborative Capabilities & Platforms Architecture	Introduction to the BDA Collaborative Capabilities	AI-UK, EADS, NLR, ULULEA + SP5 partners
5.1.2		BDA Collaborative Platforms Overview: Information Architecture and use of Standards	AI-UK, EUROSTEP + SP5 partners
5.1.3		BDA Collaborative Platforms Overview: FVP and Implementation Architecture	EADS, NLR + SP5 partners
6.1.1	BDA Collaborative Capabilities demos	Executing dynamic and distributed processes	NLR, ENGS,UCRAN
6.1.2		Simulation Quality Capabilities and informed decision support	EADS, AI-F, ISPACE, ONERA, SNECMA
7.1.1		Simulation Integrator Capability	EADS, DS, SNECMA, NLR, MSC, UCAM
7.1.2		Joined-up model driven collaboration	ULULEA, VOLVO, EUROSTEP, ENGS, FUJITSU, UNINOVA
7.1.3		Architecture and system-level behavioural representation	EADS, DS, LMS, AI-F
5.2.1	M&S - Model preparation	Model Reduction Methodologies	ULIM, THALES, AI-D
5.2.2		Automated efficient meshing	TRN, UBELFAST, RR-UK
5.2.3		CAD cleaning towards fluid domain meshing	AI-F, SIEMENS
5.3.3	M&S - Surrogate Modelling	Surrogate modelling using helicopter engine model	ECPTR,TM, IRIAS
6.2.1		Surrogate modelling to support assessment of a flexible engine during the aircraft preliminary design phase	NLR, RR-D
7.2.1		Parameterisation, surrogate modelling and Whole Engine Thermo-Mechanical Optimisation - S2T3	USOTON, RR-UK, TRN, CIMNE, UBELFAST
5.3.1	M&S - Optimisation	Bi-level aero-structural pylon design, Stiffness Optimisation and composite Pylon design	ONERA, SAAB, SAMTECH
5.3.2		LES Modelling for Aerothermal Predictions Behind a Jet In Cross-Flow	CERFACS
6.2.2		Low-fidelity Robust Optimization For Engine Requirements and Bi-Level Parametric & Topology	SAMTECH, ONERA
6.2.3		Helicopter mission analysis for engine pre-design phase	TM, ECPTR, EAI, SNECMA, UNTUA
6.4.1	M&S - Multi-Physics	NX Coupled Physics Analysis (Thermal-Structural Mapping	AI-F, SIEMENS
6.4.2		Interoperability Capabilities – Multiple Vendor Simulation Process	ANSYS, SIEMENS, AI-F, MSC, ECPTR
6.4.3		CFD database reduction methodologies	FLUOREM
7.2.2		WAVE – Improvement of multi-physic capabilities regarding simulation of water and hail ingestion	UNTUA, SNECMA
7.3.1-7.3.2	Project Technical Integration	Introduction and CRESCENDO Systems Engineering Database	AI-F, RR-UK, EADS
7.3.3		MBDA Standards	ALENIA, EUROSTEP, AFNOR
7.3.4		BDA e-learn portal and Conclusion	EADS, UNTUA, ULULEA, UNINOVA

Table 5: M26 PDW results presentations / demonstrations (part 2)

M38 CRESCENDO Forum presentations and marketplace

Results Session theme	**Session ref**	**Presentation / demo title**	**Presenting and Contributing Partners**
FORUM WELCOME and INTRODUCTION	0.1	**BDA vision, overview of CRESCENDO project results and Forum organisation**	**AI-UK, NLR, VOLVO, AI-F, SNECMA, ECPTR**
KEYNOTES	0.2	**Keynotes from Aeronautical Industry (Airbus, Rolls-Royce, Volvo Aero Corp) and IT vendors community (Eurostep et al)**	**AI-SAS, RR-UK, VOLVO, EUROSTEP** (+ DS, MSC, SIEMENS, LMS, VINCI, ANSYS, TRN)
MARKETPLACE and BUFFET LUNCH	0.3	**First MARKETPLACE visit for demonstrations of CRESCENDO results**	All consortium partners
BDA collaboration and engineering methods for POWER PLANT INTEGRATION	1.1.1	**Collaborative approach to manage maturity indicator for design convergence between Airframe- & Engine-Manufacturer**	**AI-F, DLR, NLR, RR-D**
	1.1.2	**Introducing Value-driven Design Methods in Engineering Optimisation – Comparing Design Strategies**	**AI-F, EADS, RR-UK, UCRAN, ULULEA, USOTON, VOLVO**
BDA collaboration and engineering methods for VALUE GENERATION	1.2.1	**Value Driven Design methodology**	**VOLVO, AI-UK,** EADS, RR-UK, ULULEA, USOTON, UINSAT, PYRAMIS, UCAM, UCRAN, SIEMENS, DS, EUROSTEP
	1.2.2	**Implementing a Value Creation Strategy**	**EADS, DS,** VOLVO, AI-UK, RR-UK, ULULEA, USOTON, UINSAT, PYRAMIS, UCAM, UCRAN, SIEMENS, EUROSTEP
BDA collaboration and engineering methods for THERMAL ARCHITECTURE	1.3	**Thermal stakes in aircraft development; a new aircraft thermal architecture capability**	**AI-F, EADS, DS, LMS,** VINCI, MSC
BDA collaboration and engineering methods for POWER PLANT INTEGRATION	2.1	**Collaborative Robust Engine Design Optimisation (CREDO)**	**RR-D, RR-UK, MTU, UBRAND, AVIO, USALENTO, UTORINO, IRIAS,** DS, EUROSTEP, SNECMA, AI-UK
BDA collaboration and engineering methods for VIRTUAL TESTING	2.2.1	**Introduction to Virtual Test and Virtual Certification**	**ECPTR, ULINK, EADS, SAAB,** AI-UK, AVIO, SNECMA, SHORTS, PARAGON, ISPACE
	2.2.2	**Energy Model Integration and Uncertainty Analysis**	**ULINK, SAAB,** AI-D, NLR, DS, LMS, EUROSTEP
	2.2.3	**Fault Detection of electrical systems towards validation of simulation data**	**PARAGON,** SAAB, ULINK, NLR
BDA collaboration and engineering methods for THERMAL ARCHITECTURE	2.3	**Developing the thermal aircraft along the lifecycle**	**AI-F, MSC, VINCI,** ALENIA, IAI, THALES, EUROSTEP, EADS
BDA collaboration and engineering methods for THERMAL ARCHITECTURE	3.1	**APU Compartment preliminary thermal design**	**IAI,** AI-F, EUROSTEP, MSC
BDA collaboration and engineering methods for POWER PLANT INTEGRATION	3.2	**Collaborative approach to manage Pylon Trade-Off Studies**	**AI-F, ONERA, SAAB,** EUROSTEP, MSC, NLR, SAMTECH

Table 6: M38 FORUM results presentations / demonstrations (part 1)

Results Session theme	**Session ref**	**Presentation / demo title**	**Presenting and Contributing Partners**
BDA engineering methods for SURROGATE MODELLING & ROBUST OPTIMISATION	3.3.1	**Surrogate Modelling Methods**	NLR, IRIAS
	3.3.2	**Optimisation Strategies**	IRIAS, SAMTECH
	3.3.3	**Robust Design Optimisation methods**	UCRAN, IRIAS, RR-D, SAMTECH
BDA collaboration and engineering methods for THERMAL ARCHITECTURE	4.1	**Aircraft Thermal Design; Advanced integration of equipment**	AI-F, AI-D, ALTRAN, ISPACE, THALES, ULIM, MSC, SIEMENS
BDA engineering methods for POWER PLANT PERFORMANCE	4.2.1	**Enabling Capabilities to improve answer in Engine Performance Request for Proposal (EPRfP)**	TM, EAI, UNTUA, ECPTR
	4.2.2	**Advances in aero and vibro-acoustic modelling and simulation**	AI-F, CERFACS, FFT, MSC, ONERA, SNECMA
BDA engineering methods for POWER PLANT OPTIMISATION	4.3.1	**Better Business and Reduced Emissions through Whole Engine Design Optimisation**	RR-UK, USOTON, TRN, UBELFAST, CIMNE, UNTUA
	4.3.2	**Bi-objective optimization of pylon-engine-nacelle assembly including Fan Blade Off event**	ONERA, AI-F, RR-UK, SHORTS, USOTON
TRAINING	5.1	**Envisioned BDA training - overview and next steps**	EADS, ULULEA, UNINOVA, UNTUA + all consortium partners
MARKETPLACE and BUFFET LUNCH	5.2	**Second MARKETPLACE visit for demonstrations of CRESCENDO results**	All consortium partners
BDA collaboration capabilities for EXTENDED ENTERPRISE	6.1	**Enabling Secure Collaboration**	VOLVO, AI-UK, EUROSTEP, DS, MSC, SIEMENS
BDA collaboration and engineering methods for POWERPLANT INTEGRATION	6.2	**Collaborative engineering by distributed simulation in power plant thermal integration**	AI-F, SIEMENS, DS, EUROSTEP, MSC, SHORTS, SNECMA
BDA collaboration and engineering methods for VIRTUAL TESTING of THERMAL ARCHITECTURE	6.3.1	**Introducing Virtual Testing for Fire Protection Certification**	AVIO, ISPACE, SIEMENS, USALENTO
	6.3.2	**Simulation for thermal equipment qualification (Climatic virtual Testing)**	ISPACE, THALES, EADS, ONERA, AI-F
BDA collaboration capabilities for EXTENDED ENTERPRISE	7.1	**Supporting Behavioural Architects with simulation quality management and risk informed decisions**	EADS, AI-UK, DS, LMS, AI-F, MSC, VINCI, ECPTR, ISPACE, ONERA
BDA collaboration and engineering methods for POWERPLANT INTEGRATION	7.2	**Innovative Product Integration Process capabilities in a collaborative environment**	SNECMA, DS, SIEMENS, VINCI, AI-UK, SHORTS, UBELFAST, UNINOVA
BDA engineering methods for MODEL PREPARATION and MULTIPHYSICS ANALYSIS	7.3.1	**Improved simulation capabilities for Water and Hail Ingestion within engines**	SNECMA, UNTUA, ONERA
	7.3.2	**Efficient geometry cleaning process and fluid-structure thermal coupling approaches**	AI-UK, AECI (AI-SAS), SIEMENS, ANSYS

Table 7: M38 FORUM results presentations / demonstrations (part 2)

Results Session theme	**Session ref**	**Presentation / demo title**	**Presenting and Contributing Partners**
BDA collaboration capabilities for EXTENDED ENTERPRISE	8.1	**Executing Collaborative Simulations**	NLR, AI-UK, ENGS, UCRAN, DS, EADS, MSC, SAAB, UCAM
BDA collaboration and engineering methods for VIRTUAL TESTING of POWERPLANT PERFORMANCE	8.2.1	**Engine Nacelle Anti-icing – A Quicker way to Certification**	SHORTS, ENGS
	8.2.2	**Matching process between simulation data and physical test results for engine performance studies**	SNECMA, EAI, ISPACE
BDA engineering methods for MODEL PREPARATION and MULTIPHYSICS ANALYSIS	8.3.1	**Coupled Multi-physics approach for a High Fidelity integrated model.**	AI-F, CERFACS, ONERA
	8.3.2	**Coupled simulation for high- and low-pressure turbine optimisation**	MTU, RR-D
TRAINING	9.1	**Behaviour Architecture training course objectives**	EADS, DS, LMS, AI-F, MSC, VINCI, other WP5.2 partners
TRAINING	9.2	**Simulation Integration training course objectives**	EADS, UCAM, SNECMA, AI-F, ANSYS, CIMNE, DS, EAI, LMS, MSC, NLR, SAMTECH, SIEMENS, UCRAN
TRAINING	9.3	**Simulation Quality training course objectives**	EADS, ONERA, AI-F, AVIO, ISPACE, SIEMENS, THALES, ULULEA, UNINOVA, UNTUA
MARKETPLACE	9.4	**Third MARKETPLACE visit for demonstrations of CRESCENDO results**	All consortium partners
BDA collaboration and engineering methods for VALUE GENERATION	10.1.1	**Improving Concept Down Selection by Simulating Surplus Value for a Fleet of Aircraft**	RR-UK, USOTON, ENGS, EUROSTEP
	10.1.2	**Value Visualization and decision support**	ULULEA, VOLVO, SIEMENS, EUROSTEP
	10.1.3	**Change Prediction in Value Generation**	UCAM, VOLVO
BDA engineering methods for MODEL PREPARATION and MULTIPHYSICS ANALYSIS	10.2.1	**Geometric reasoning for automatic efficient meshing**	TRN, UBELFAST, RR-UK, USOTON
	10.2.2	**Thermal Model Integration Capability applied to Power Plant**	AI-D, ALTRAN, MSC, SHORTS, SNECMA, SIEMENS
	10.2.3	**Multi-physics analysis of a whole engine model including piezoelectric damping for rotor bearing**	DLR, SNECMA, VOLVO
BDA collaboration and engineering methods for THERMAL ARCHITECTURE	10.3	**Environmental Control System Preliminary Design and Cabin Integration**	ALENIA, USALENTO, PARAGON, NLR, MSC, UTORINO
FORUM CONCLUSIONS	11	**Summary of key messages, way forward towards exploitation of results and opportunity for Q&A with Forum participants**	AI-UK, NLR, VOLVO, AI-F, SNECMA, ECPTR

Table 8: M38 FORUM results presentations / demonstrations (part 3)

		03	02	01		24		
		IRIAS - MACROS for data analysis and multidisciplinary optimization	**Cranfield University** - Aircadia in the context of CRESCENDO	**VOLVO** et al - Enabling secure collaboration	**Entrance**	Spare stand		
04	**AI-F, RR-UK, NLR** et al - Preliminary Multi-disciplinary Powerplant Design: Robust Optimisation, Pylon Architecture		27	26	25		**SIEMENS** - Contributions to CRESCENDO results	23
05			**AI-UK** - BDA Architecture	**EADS, UNTUA, RR-UK, AIRBUS** - CRESCENDO Systems Engineering, Standards, E-learning and Exploitation			**DASSAULT SYSTEMES** - BDA implementation with V6	22
			EUROSTEP - Collaborative hub for CRESCENDO using Share-A-space™	**VINCI** - Semantic Data Management - Enabler for a collaborative platform	**ANSYS** - integration capabilities for multi-vendor processes			21
			28	29	30		**AI-F** et al - Developing thermal aircraft along the lifecycle	20
06	**TRN** - Meshing and idealisation		Food and drinks buffet				**MSC** - Servicing BDA innovations	19
07	**USOTON**, RR-UK et al - Whole Engine Design Optimisation		33	32	31		**ALENIA** et al - Comprehensive ECS Design, Cabin Integration, and Comfort Valuation	18
08	**AI-F**, SIEMENS - Distributed Simulation in Powerplant Thermal Integration		**VOLVO, RR-UK, AI-UK, EADS, UINSAT, ULULEA, USOTON** - Value Driven Design Methodology & Capabilities		**University of Cambridge** - Change Propagation in Workflows		**PARAGON** - Fault Detection of Electrical Systems	17
09	**SNECMA, UNTUA** - Simulation of Water and Hail Ingestion in Engines		**ALTRAN** - New capabilities for thermal trades	**LMS SAMTECH** - Contributions to CRESCENDO results	**LMS IMAGINE** - Federative platform for architecture driven system engineering		**FLUOREM** - Turb'Opty - CFD database reduction methodology	16
10	**EAI** - PROOSIS capabilities		34	35	36			
		Spare stand	**AI-D, AECI**, THALES, ULIM - Model Reduction Methodologies	ISPACE, THALES - Virtual means of compliance for Thermal Equipment Design	**ISPACE** - Physical and Virtual testing – Simulation model validation	AI-F, CERFACS, ONERA - LES for Aerothermal Predictions		
		11	12	13	14	15		

Table 9: M38 FORUM Marketplace map

Appendix C – CRESCENDO Results Catalogue Classification

Ref-id	RESULT category title
BDA Collaborative Capabilities	
R35	Collaborative approach to manage pylon trade-off studies
R38	Collaborative organisation for supporting multi-disciplinary optimisation process
R44	Setting-up a professional solution for collaborative workflow access
R51	The BRICS capability to support cross-enterprise workflows in compliance with security constraints
R52	Behavioural Digital Aircraft Capabilities Enabling Secure Collaboration
R53	Behaviour Architect Capability
R58	Architect Dashboard
R62	Collaborative approach to manage maturity indicator for design convergence between airframe & engine manufacturer
R78	Semantic Data management applications
R101	Knowledge management: report and analyse collaborative decision
R108	Surrogate modelling for the structural optimisation of a composite nacelle fan cowl door
BDA M&S Capabilities	
1	**BDA Behaviour Architect Capabilities**
R1	Global local optimization
R2	Surrogate modelling with MACROS toolset
R3	Novel effective robust optimization methodology
R4	Interactive Robust Multi-objective Optimisation
R12	SFC surrogate model used in bi-objective optimization
R13	Engine mass surrogate model used in bi-objective optimization
R14	Collaborative surrogate-based optimization of a coupled turbine model
R16	Rapid Preparation of Geometry for Analysis - Synchronous Technology
R19	Test Data Process and Management
R20	Integration of surrogate models into A/C level simulation of engine secondary power offtakes
R21	Fast Robust Design Optimisation Methods
R23	Enabling capability to improve engine performance request for proposal (Erfp)
R24	Surrogate modelling for engine assessment and requirements maturing during the aircraft preliminary design phase
R25	Model Reduction Strategies
R27	Robust optimisation through polynomial chaos expansion surrogate modelling
R29	Automated efficient meshing
R30	Whole aerothermal virtual (3D) engine model (WAVE)
R31	3D model engine set-up methodology
R32	Development of rain & hail ingestion models for engine performance simulations and integration in PROOSIS
R40	Specification of Behaviour Architect role
R47	2D thermo-mechanical rotor model
R50	Change propagation in workflow
R75	ECS Preliminary Design and Cabin Integration
R79	Bi-level parametric and topology optimisation
R86	Numerical methods for the modelling and propagation of uncertainty
R96	Auxiliary Power Unit (APU) compartment preliminary thermal design
R102	BDA Architecture - Business Object Model
R103	BDA Data Services - Web Service Definition and Services
R104	Dynamic (Re)Configuration of Simulation Workflows
R105	Collaborative optimisation and the automated execution of distributed workflows involved (Isight/Fiper)
2	**BDA Simulation Integration Capabilities** and related simulation capabilities
R5	Multi-physics analysis and optimization of active damping for engine rotor bearing
R11	Bi-objective optimization of pylon-engine-nacelle assembly including Fan Blade Out event
R15	Integrator environment to support the product definition
R17	Automated Coupled Analysis
R22	Coupled CFD High Pressure Turbine (HPT)-Low Pressure Turbine (LPT) simulation technique
R26	Functional-driven simulation
R33	Definition of Simulation Intent concepts to support knowledge capture and use in the simulation
R45	Coupled multi-physics approach for a high fidelity integrated model
R46	Whole engine thermo-mechanical design optimisation
R49	Integrated thermal model enabler, including COTS model conversion and integrated thermal model set up and run
R63	Efficient geometry cleaning process
R64	Fluid-structure thermal coupling approaches
R76	Human Ontology Model for its Environmental Response (HOMER) - Environmental Control System (ECS)
R80	Aero-acoustic methods for installed Jet-Noise
R81	Aero-vibro-acoustic methods for counter rotating open rotor (CROR)
R82	Collaborative engineering by distributed simulation in power plant thermal integration
R85	Energy model integration and uncertainty analysis
R90	Thermal integration of equipment
R92	Global Thermal Aircraft (GTA)
R97	Better business and reduced emissions through whole engine design optimization

Table 10: CRESCENDO Results Catalogue Classification (part 1)

Ref-id	RESULT category title
BDA M&S Capabilities	
3	**BDA Simulation Quality Capabilities**
R28	Quality Method to ensure integration consistency
R54	BDA Credibility Assessment Scale (CAS) dashboard with quality indicators
R91	Trade-off tool for evaluating thermal design
BDA Methodologies	
1	**Value generation methodology**
R7	Value-driven Design Methods in Engineering Optimisation - Comparing Design Strategies
R8	Customer Oriented Design Analysis (CODA)
R9	Implementing a Value Creation Strategy
R18	Value contribution through visualization in Design
R48	Value-driven design methodology
R59	Value visualisation and decision support
R60	Surplus Value Model
R61	SimCad-SVM interface
2	**Virtual testing methodology**
R36	Simulation for certification
R37	Matching process between simulation data and physical test data for engine performance studies
R65	Fault detection process of electrical systems
R94	Climatic virtual test
R98	Generic process for Virtual Testing & Virtual Certification
R99	Virtual Test (VT) Validation Process template
R100	Dynaworks thermal data connector
Training Material and Management tool and methodology	
R57	CRESCENDO SEDB (Systems Engineering Data Base)
R70	High level objectives assessment methodology
R74	BDA e-learning portal
R107	RTD impacts analysis methodology
Standardisation	
R69	CRESCENDO standards recommendation
R106	BDA DEX and associated information

Table 11: CRESCENDO Results Catalogue Classification (part 2)