1 Publishable summary

1.1 CRESCENDO context, objectives and expected results

Context and Challenges

The “Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation” (CRESCENDO) project was launched in May 2009 and ended in October 2012. Co-funded under the European Union 7th framework programme, the project is led by Airbus and brings together 59 organisations from 13 different countries. Figure 1 below shows the major aeronautics industry companies, IS/IT solutions and services providers, research centres and academic institutions, that together form the overall 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.

Hence, the CRESCENDO project addresses the critical challenge to ensure product maturity at entry into service, by improving the management and evolution of the “Behavioural Digital Aircraft” Dataset from concept to certification.

High Level Objectives and Impact

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 multidisciplinary teams working as part of a collaborative enterprise, in order to develop new aeronautical products in a more cost and time efficient manner.

The following High-level Objectives were taken as a guide to assess the contribution of the CRESCENDO project results, once deployed and exploited:

• 10% reduction of development lifecycle duration and cost;

• 50% reduction in rework, and finally;

• 20% reduction in the cost of physical tests.

These objectives also serve to position the CRESCENDO project with respect to the Quality and Affordability challenges of the initial Vision 20201 and subsequent European aeronautical industry Strategic Research Agenda2, 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”.

Hence, the CRESCENDO results are expected to provide the means to manage and mature the behavioural characteristics of the virtual product across the extended enterprise, with all of the requested functionality and components in each phase of the product development life cycle.

The CRESCENDO project has made its results available to the aeronautics supply chain and related scientific community through a considerable number of publications, dissemination activities including the CRESCENDO Forum and other existing industry networks, the creation of an e-learning platform and overall results catalogue, and follow-on collaborative research projects with European and national funding support.

Further information about the CRESCENDO project will be found on the CRESCENDO public website: www.crescendo-fp7.eu. At the time of writing this report, the public website still required some updating to include all the finally agreed publishable results. When completed, the public website will remain live for a minimum of three years after project end i.e. until end October 2017.

**Expected Final Results**

The major result of the CRESCENDO project has been to develop the foundations for what is referred to as the “**Behavioural Digital Aircraft**” (BDA). Figure 2 below evolved during the project and was used extensively at various dissemination events to illustrate three key concepts associated with the BDA in the extended enterprise.

![Figure 2: Behavioural Digital Aircraft - Dataset, Platforms and Teams](image)

1. The **BDA dataset** is considered as a multi-partner, multi-level, multi-discipline, multi-criteria behavioural digital representation of the evolving Aircraft and all its constituent systems and sub-systems. A single, but distributed, BDA dataset would typically exist for a given major aircraft development program.

2. Multiple **BDA platforms** implement collaborative services solutions and behavioural multi-physics simulation capabilities to manage, manipulate, preserve, re-use and enrich all the models & associative data needed to create, evolve & mature the BDA dataset. Several instances of BDA platforms would typically exist across the collaborative enterprise. The aim for CRESCENDO is to define a generic BDA architecture specification that any given platform implementation should comply with. However, different aircraft and engine manufacturers, partners and suppliers may need to use only part of the complete functional specification, and may choose different vendor solutions to implement the BDA platform for their organisations.

3. Finally, it is envisaged that there could typically be thousands of potential **users**, collaborating in **teams** across the extended enterprise, creating and sharing their information more efficiently through the BDA platforms, to create and build the BDA dataset. Such users range from aircraft program architects and chief engineers, through to teams of design, modelling and simulation engineers, supported by IS/IT specialists.
Figure 3 below presents another view, illustrating the seven areas of interrelated technical results arising from the CRESCENDO work packages.

In order to create the BDA dataset, CRESCENDO results provide innovations to enable collaborative modelling and simulation at two levels:

- **BDA collaborative capabilities** to address the challenges for managing distributed data, processes and infrastructure, including definition of a generic Business Object Model, web services and DEX specification built on ISO standards; secure collaborative workflows; and creation of a decision environment for aircraft behaviour architects to orchestrate trade studies, with dashboards to monitor progress and assess quality of simulation results.

- **BDA engineering methods** to address the challenges for more effective behavioural modelling methods and simulation processes, in such areas as model preparation using automated meshing and geometric reasoning techniques; surrogate and reduced order modelling; multidisciplinary optimisation strategies; multi-physics coupling with some focus on thermal fluid-structure interactions and advances in aero-acoustic-vibration computational modelling.

In order to apply and validate these enabling technologies, the CRESCENDO project also delivers results to illustrate:

(a) The ability of the BDA capabilities to be applied in the **preliminary design, detailed definition, test and certification** phases of the product development lifecycle.

(b) The ability of the BDA capabilities to be applied for technically complex and challenging areas of modelling and simulation on which CRESCENDO will provide improvements, referred to in CRESCENDO as the “Use Cases”.

Four Use Case areas were considered: Value Generation, Thermal Aircraft, Power Plant Integration, and Energy Aircraft (the scope of this last one was reduced to focus on Virtual Testing aspects only). Illustrated in Figure 4, the Use Cases are further decomposed into 17 Test Cases that represent realistic scenarios for specific decisions to be made within one of these phases of the product development lifecycle.
As well as developing innovations, in specific behavioural modelling and simulation capabilities, the Use Cases and Test Cases serve to demonstrate the project results by showing the applicability of the BDA platforms capabilities to support this range of representative and realistic situations.

Essentially, the result in the preliminary design and earlier definition phases will be “design driven by simulation”, transitioning towards “design validated by simulation” in the later test and certification phase of the lifecycle.

**Figure 4**: Use Cases and Test Cases provide realistic scenarios to validate the BDA capabilities

**CRESCENDO project work plan**

The description of work was carried out through six “sub-projects”, summarised below, and further divided into a total of 27 work packages, as shown in Figure 5.

- **SP0 “Consortium Management”** provided the contract management, organised project level milestone events, and also coordinated the dissemination of CRESCENDO results and the preparation for exploitation of results.
- **SP1 “Overall Technical Management and Integration”** ensured the technical convergence towards the High Level Objectives, in terms of benefits assessment, overall use case integration, contribution to standards, and training activities.
- **SP2 “Preliminary Design”, SP3 “Detailed Definition” and SP4 “Virtual Testing & Virtual Certification”** each represented these phases of a typical product design cycle. Their generic roles were to define the requirements for the BDA enabling capabilities, and to develop the engineering methods and simulation processes needed by the test cases, when not already pre-existing.
- **SP5 “BDA Enabling Capabilities”** developed all the capabilities required to build the BDA platforms and participated in the validation plan. This extends from generic services to the implementation of a federated validation platform to demonstrate the test cases.
Finally, the implementation of the work plan was built on an iterative approach, also illustrated in Figure 5 below. Three major project phases were defined for Proof-of-Concept (M1 to M15), Prototype (M16 to M30) and Validation (M31 to M42), with criteria and targets set in each phase to ensure the progressive completeness and maturity of requirements definition, prototypes development and validation demonstrations of the project results.

![Figure 5: CRESCENDO WBS with Three project phases to progressively mature results](image)

1.2 CRESCENDO Project progress towards objectives

![Figure 6: Project phases and milestones to steer progress towards expected results](image)
The overall progress towards objectives is depicted in Figure 6, in terms of the project milestones (MS0 to MS8) and the principal achievements in each of the three major phases of the CRESCEndo project. With reference to Figure 6, the following paragraphs describe the progress made during each phase in more detail.

**Summary of progress made during the Proof-of-Concept phase (M1 to M15)**

The CRESCEndo Systems Engineering Database (SEDB) was established, using a set of “templates” to provide a consistent format for gathering requirements across the Use Cases, Test Cases & BDA capabilities, and linking these with expected benefits and contributions towards the high level objectives.

An overall Systems Engineering framework for designing the BDA architecture was established and the first phase of requirements and functional analyses were completed for the BDA enabling capabilities.

The test cases’ modelling & simulation scenarios were defined, with detailed simulation process maps and the associated models & methods. Links between test cases were identified. More generic process descriptions for lifecycle phases represented by SP2, SP3 and SP4 were also described.

The key step to complete the concept phase was the first 2-day BDA awareness workshop in June 2010, improving (a) visibility of the preliminary implementation of BDA capabilities started by individual and combined technology providers; and (b) the requirements capture & feedback between SP5 and SP2/3/4.

The following assessment was made versus the targets for the Proof-of-Concept phase:

- **Overall requirements completeness & maturity = 59%** (versus 75% target).
- **Overall development completeness & maturity = 22%** (versus 35% target).
- **Overall validation completeness & maturity = 5%** (versus 20% target).

However, the conclusion was that the project was globally 3 months behind schedule.

**Summary of progress made during the Prototype phase (M16 to M30)**

Requirements were finalised. Considerable effort was made through cross-project integration teams (involving representatives from all sub-projects) to understand, refine and improve the clarity of requirement statements, and capture these in the agreed format to populate the CRESCEndo Systems Engineering database. This was done in 2 main areas: those requirements specifically targeting BDA collaborative capabilities and platforms development, and those targeting behavioural modelling and simulation methods & technology improvements.

An intermediate BDA platforms architecture specification was completed, following the BDA architecture framework defined in Period 1 and adopting a three-layer information model including business concept model, business object model, and data model based on ISO standards 10303-233 (Systems Engineering) and 103030-239 (Product Life Cycle Support).

A deeper functional analysis of BDA capability areas (Model Store, Simulation Factory, Quality Lab and Enterprise Collaboration) was performed to explicitly map the identified functions to agreed requirements and emerging solution implementations (prototypes). As a result, 10 key areas for innovation in the BDA capabilities were identified.

Demonstration and validation plans for the test cases were defined and a considerable effort placed on completing an intermediate integration at Use Case level for the Thermal Aircraft and Power Plant Integration.
The emerging business value of the overall BDA approach was demonstrated at the M26 BDA Prototypes Demonstration Workshop (PDW) 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 in Figure 3. A table, listing the 50 presentations and partners involved, is included in the Period 3 report and will be published on the public website. There was positive feedback on the outcomes from the M26 PDW including 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”.

In addition, the prototype phase also saw a ramp-up in dissemination activity, with 23 publications, including the CRESCENDO presentation “Developing the BDA”, delivered by the project coordinator at the EC sponsored Aerodays (Madrid, March 2011), see http://www.cdti.es/recursos/doc/eventosCDTI/Aerodays2011/3D1.pdf.

The following assessment was made versus the targets for the Prototype phase:

- Overall requirements completeness & maturity = 100% (versus 100% target).
- Overall development completeness & maturity = 78% (versus 80% target).
- Overall validation completeness & maturity = 60% (versus 40% target).

This assessment closed the prototype phase at M30 and confirmed the conclusion from the 2nd annual contract review, that overall progress was 6 months behind schedule and therefore a corresponding extension was negotiated.

**Summary of progress made during the Validation phase (M31 to M42)**

Progress during the Validation phase was split in two distinct parts: from M31 to M38, leading to the CRESCENDO Forum; and from M39 to M42, leading to the Final Review.

A major advance, from prototype to validation phase, has been the final implementation of the Federated Validation Platform (FVP). This is the network of industry labs connecting various partner sites, as shown in Figure 7, which has allowed the installation and functional verification of the prototype solutions. Then, the FVP has been used to validate the application of the BDA collaborative capabilities and engineering methods by running the various test cases’ scenario processes in more realistic environments. This was a main focus of activity for the preparation of the CRESCENDO Forum.

![Figure 7: CRESCENDO Industry lab network and Federated Validation Platform](image-url)
Figure 8: Photographs from the M38 CRESCENDO Forum
One of the most significant events of the project, the M38 CRESCENDO Forum (see Figure 8) 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. The Forum handbook (154 pages), produced as a guide to the 45 technical results presentations and 30 marketplace stands (including 82 posters), will be published on the public website and a table listing the presentations and partners involved is also included in the Period 3 report.

The validation phase has also seen a significant increase in other dissemination activity, with 53 further publications for journals, conferences or seminars and 6 university theses linked with the CRESCENDO results. Four additional industry and supply chain dissemination 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.

In the final period, the overall BDA architecture specification was completed and a standardisation strategy was initiated. This includes all the detailed Business Object Model (BOM) documentation (defined in UML) that provides the vocabulary, grammar and syntax for a BDA collaboration standard. A design approach for information web services was also shown to be efficient, re-usable and accessible to implementers. To promote a family of Data Exchange Specifications (DEX) based on the BDA BOM, each business object class in the BOM becomes a template in PLCSlib (a SysML based environment for defining DEXs). So far, there are 60 templates defined (as shown in Figure 9) and two specific DEX have been built for “AssociativeModelNetworks” and “ModelInstances”. Started in CRESCENDO, this standardisation strategy is being tracked and increasingly supported by the EADS-SSC (Strategic Standards Committee) and the ASD-SSG (AeroSpace & Defence Industries Association of Europe Strategic Standardisation Group) for wider exploitation e.g. see http://www.asd-ssg.org/radar-chart.

![Figure 9: BDA Business Object Templates in PLCSlib](image-url)
Considerable effort was placed on creating content for the BDA e-learning portal. This is a Moodle platform web-based application (http://elearn.llt.ntua.gr/), providing access to the deployment guidelines, training materials and wiki glossary developed by the CRESCENDO partners, as shown in Figure 10. The purpose is to facilitate deployment and exploitation of the CRESCENDO results. It was agreed that the National Technical University of Athens will continue to maintain the BDA e-learning portal for a period of 3 years (up to October 2015) but the access and content remains consortium confidential.

Another achievement from the validation phase has been the compilation of a final results catalogue. The public version consists of a user guide, excel spreadsheet, and complementary illustrated document. These will be published on the public website, providing contacts and a classification, as well as short descriptions and maturity assessments, for 81 exploitable results from the CRESCENDO project.

![BDA e-Learning Portal Welcome Page](image)

Figure 10: BDA e-learning portal welcome page

The following assessment was made versus the targets for the Validation phase:

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

An assessment of the CRESCENDO contribution versus high level objectives is summarised in Table 1. The figures are derived from data collected in the CRESCENDO SEDB and the utility value analysis performed by WP1.2. 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.
The validation gap at M38 is not seen to be critical and the overall assessment is considered a creditable outcome for such an ambitious research project.

<table>
<thead>
<tr>
<th>CRESCENDO High Level Objective</th>
<th>Target HLO reduction for CRESCENDO contribution</th>
<th>Assessment of achievable contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development Life Cycle Cost (LCC)</td>
<td>10%</td>
<td>5.5 - 9.5%</td>
</tr>
<tr>
<td>Development Life Cycle Time (LCT)</td>
<td>10%</td>
<td>4.4 - 9.2%</td>
</tr>
<tr>
<td>Rework</td>
<td>50%</td>
<td>30 - 47%</td>
</tr>
<tr>
<td>Physical Testing Costs (PTC)</td>
<td>20%</td>
<td>16 - 21%</td>
</tr>
</tbody>
</table>

Table 1: Assessment of CRESCENDO contribution versus High Level Objectives

The following concluding remarks, from the CRESCENDO Forum, remain valid:

- CRESCENDO has enabled the BDA dataset, with new processes and engineering methods:
  - Providing a methodology for value-driven design to meet stakeholders expectations;
  - Eliminating risk early in preliminary design and more accurately predicting the detailed operational and functional behaviour through sophisticated multi-physics analysis and optimisation strategies;
  - Providing a virtual testing methodology to reduce the need for repeat physical testing and prepare for certification based on simulation.

- CRESCENDO has enabled the BDA enterprise, with new software functionalities impacting the IS vendors’ roadmaps and real collaborative engineering capabilities to support multiple partners and multi-disciplinary teams working across the extended enterprise.

The CRESCENDO project has been a collaborative team effort, and the consortium can look forward to benefit from the demonstrated “innovations in collaborative modelling & simulation to deliver the Behavioural Digital Aircraft”. Such innovations in the Aircraft Product Development Process remain key to sustaining competitive business performance for the industry & supply chain, and to meeting the challenges from the market and society. Finally, the months following the CRESCENDO project continue to indicate that the BDA vision is becoming reality in both the IS providers’ solutions and in the industrial process context.