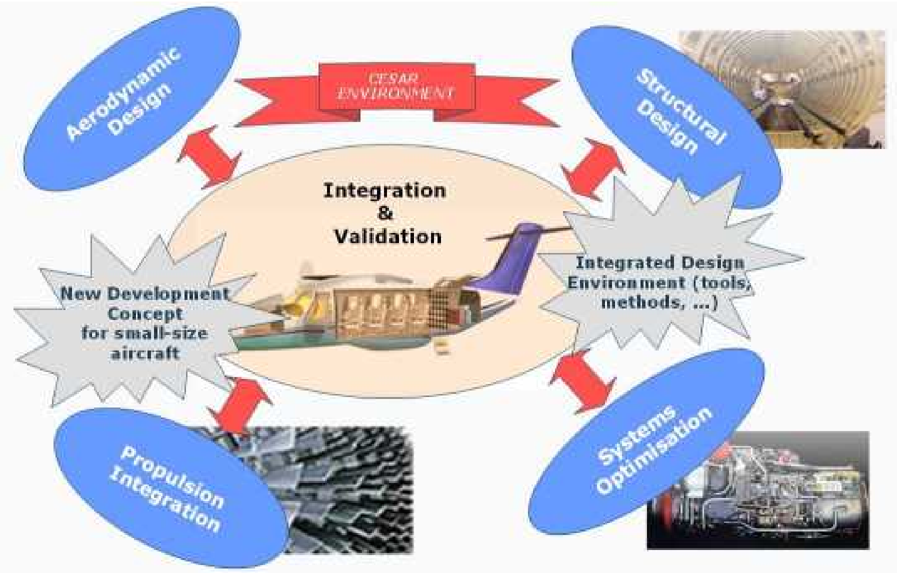
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

A practical approach for the coordination of multi-partner engineering jobs in the design of small aircraft



Problem area
Europe has a long tradition of developing and building aircraft. European aircraft manufacturers are successful in the whole range from small business to large passenger aircraft.

The new EU member states such as the Czech Republic, Poland and Romania recognised business opportunities for small and medium size commercial aircraft. This sector, which includes also a great number of small and medium enterprises, is very important in terms of maintaining European competitiveness in aeronautics.

The EU 6th Framework Programme project "Cost Effective Small AiRcraft" (CESAR) is aimed at providing the European manufacturers of regional, commuter and business aircraft with an enhanced ability to become fully competitive in the world market of small-size commercial aircraft. The project objective is to build up a new development concept for this particular aircraft category and to improve selected technologies enabling significant reduction of time-to-market period and lowering the overall development and operational costs, while considering safety, passenger comfort and environmental impact.

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Knowledge area(s)
Aerospace Collaborative Engineering & Design
Computational Mechanics & Simulation technology

Descriptor(s)
Knowledge based engineering
Collaborative engineering
Secure remote information sharing
Tool chain automation

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NLR, being an important partner for Dutch aircraft industry with respect to maintaining and increasing competitiveness in the world markets, also for small aircraft such as the Gulfstream G650, is involved in the project to strengthen its relationship with the European small-size commercial aircraft industry, and to increase its knowledge on multi-partner collaborative engineering solutions in this industry.

Description of work

To respond cost-effectively and competitively to today's market demands on development time and cost reduction, the small-sized aircraft industries and their supply chains need to collaborate closely. The main collaboration tool in the project is the Integrated Design System, a platform that defines and supports an integrated, effective and efficient process for the life cycle design of small aircraft. The platform enables the small-aircraft industry to collaboratively develop and exploit complex computational models in a short period of time. It acts as a research platform for integration of technologies and for standardization and automation of computational models.

Results and conclusions

This paper presents an innovative, practical approach, which is implemented as part of the platform, that enables partners in the European regional and small-size commercial aircraft industry to collaborate effectively in the development of aircraft and hence to face the challenges of time and cost reduction. We present an industrial case study on multidisciplinary collaboration as well as the technologies that support the collaboration. The case study concerns a finite-element model updating procedure for flutter analysis models. The technologies comprise solutions for secure remote exchange of engineering information and for coordination of distributed multi-partner engineering activities. Using the case study as example, we describe how the technologies support the engineers to collaborate effectively.

Applicability

Experiences with the demonstrator described in this paper show that the combination of existing technologies for information sharing and job coordination is a feasible solution for collaboration in the scene of the European small-aircraft industry. The technologies enable the partners to effectively play their role in the multi-partner engineering jobs as part of the aircraft design and development process. The technologies are available to the partners via common tools and usual ways of working, and as such do not require large investments on supporting tools and cultural changes.
The technologies described in this paper have been demonstrated in the context of the CESAR project, but can generally be applied in multi-partner collaboration in the development of aircraft and aircraft components. The low costs make application of the technologies feasible for the small-aircraft industry in particular.

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A practical approach for the coordination of multi-partner engineering jobs in the design of small aircraft

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Summary

Aerospace industries and their supply chains need to cooperate to be able to respond cost-effectively and competitively to today's demands on reduction of development time and cost, in addition to safety and sustainability. This paper presents a new practical approach that enables partners in the European small passenger aircraft industry to collaborate effectively in the development of aircraft and hence to face the challenges of time and cost reduction. We present an industrial case study on multidisciplinary collaboration as well as the technology that supports the collaboration. The case study concerns a finite-element model updating procedure for flutter analysis models. The technology comprises solutions for secure remote exchange of engineering information and for coordination of distributed multi-partner engineering activities. Using the process as example, we describe how the technologies support the engineers to collaborate effectively.

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Contents

Abbreviations

CESAR	Cost-Effective Small AiRcraft
CWS	CESAR Conductor-Workflow System
DFR	CESAR Data File Repository
EU	European Union
FEM	Finite Element Method
GVT	Ground Vibration Test
IDS	CESAR Integrated Development System
IT	Information Technology

1 Introduction

World-wide competition in the aircraft market drives a need for continuous product improvements, to reduce aircraft development costs and time, and improve product performance. Additional challenges for the industry are set by the European Vision 2020 [1] that in the next two decades needs to meet targets on reduction of emissions, noise, costs and improved safety. All this must be achieved with expected increase in capacity and market demands. Nowadays for the European general aviation it takes on average 6 to 7 years to design, develop and fully certify a small passenger aircraft. The time reduction of the development cycle is one of the most important sources of competitive advantage. As a result, the total development costs go down and the payback period is shorter as well.

Today’s aircraft are high-quality complex structures developed by different specialized companies that constitute the supply chain of an aircraft integrator, who takes care of the overall design, development, and final construction of the aircraft. To respond cost-effectively and competitively to today’s market demands on development time and cost reduction, aerospace industries and their supply chains need to collaborate closely. This collaboration is one of the major topics in the EU 6th Framework Programme project CESAR (Cost-Effective Small AiRcraft) [2]. The project focuses on new development concepts for small-sized commercial aircraft. The major collaboration tool in the project is the Integrated Design System (IDS), a framework that defines and supports an integrated, effective and efficient process for the life cycle design of small aircraft.

In this paper we briefly introduce the IDS. We illustrate its application to an industrial aircraft engineering problem and its solution by means of a multi-disciplinary collaboration case study. The case study comprises a finite element method (FEM) model updating process for flutter analysis towards testing and certification of small aircraft. We introduce technologies for secure remote exchange of engineering information and for coordination of distributed multi-partner engineering activities. Using the case study as example, we describe how these technologies enable the distributed multidisciplinary partners to collaborate effectively, and as such respond to the needs for collaboration among European small-aircraft industries. We finally present conclusions and plans for future research.

2 Integrated design for small aircraft

The way forward for the European small-aircraft industry to meet the challenges of development time and cost reduction is to introduce innovative technologies. In the CESAR project, an integrated, effective and efficient process and supporting platform for the life cycle design of small aircraft was developed. Figure 1 presents a global overview of the platform: the Integrated Design System (IDS).

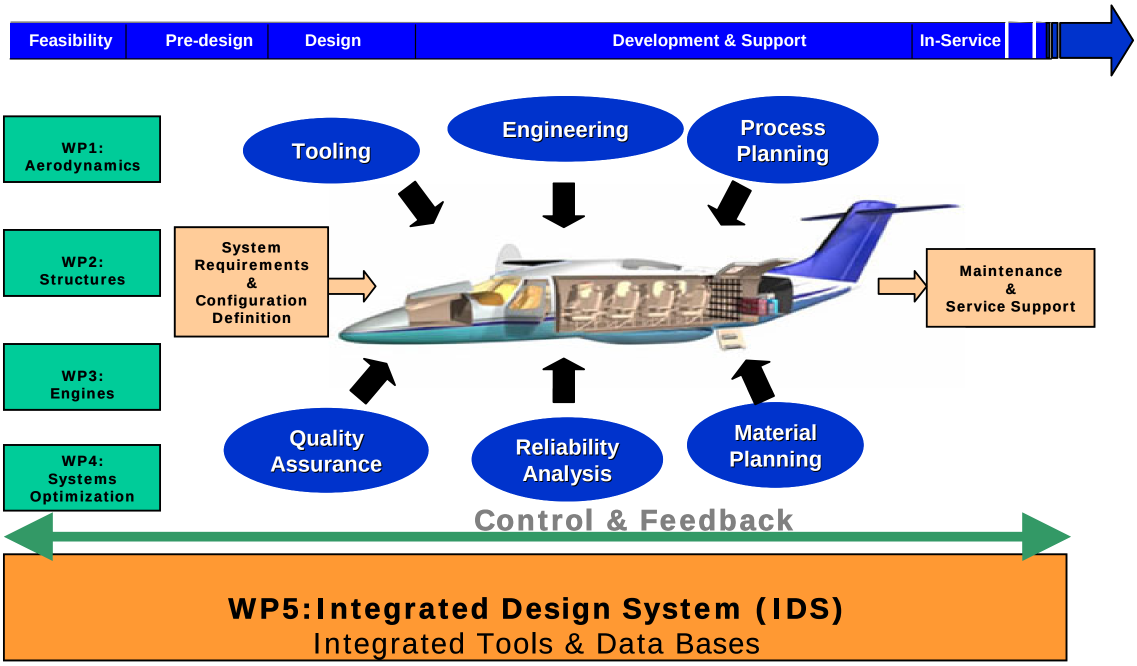

Figure 1 Global overview of the Integrated Design System (IDS) approach for small aircraft

In order to meet the challenges, the IDS is based on an evolutionary and systems engineering approach that comprises several important components that support customer specifications, conceptual design, risk analysis, functional analysis and architecture, physical architecture, design analysis and synthesis, trade studies and optimisation, manufacturing, validation and verification, delivery, life cycle cost and management. Furthermore, IDS aims to improve interaction between traditional disciplines such as aerodynamics, structures and flight mechanics and with other process-oriented disciplines. IDS also supports delocated partners working on several engineering disciplines (aerodynamics, fuselage, engine, systems) towards the whole life-cycle of a small aircraft (pre-design, design, development, operation) and to collaborate in establishing Top Level Aircraft Requirements (TLAR) definition and substantiation, preliminary design configuration, and knowledge data management for subsequent design phases. Implementation of the various engineering tools (CAD, CFD, FEM, MDO, fatigue tool, etc.) and the global set-up of the IDS is based on IT technologies for virtual collaborative environments, data sharing, and access under improved security. The users (e.g., designers, stress analysis specialists, aerodynamics engineers, and test engineers) have access to such a system as a client, with an increased level of flexibility and options according to the status of this project. Knowledge-based engineering technologies have been applied to realise a demonstrator of a virtual collaborative environment. This environment provides support for collaboration among the distributed partners, in terms of data sharing and co-ordination of multi-partner activities.

The IDS is based on and part of a scenario, where the product to be defined is analysed according to a set of requirements. This starts with mission and imposed functionalities, safety, customer satisfaction, direct and indirect operating costs, time to market and certification standards.

The platform enables the small-aircraft industry, such as airframers, engine producers, system suppliers, to collaboratively develop and exploit complex computational models in a short period of time. It acts as a research platform for integration of technologies and for standardization and automation of computational models. It supports the application of digital simulation and multi-disciplinary design optimisation that are required for efficient design of state-of-the-art products. As such, it supports distributed aerospace partners, each specialized in its own engineering disciplines, to collaborate closely and to be competitive. In the next section we will describe a case study that demonstrates its applicability.

3 A case study on multi-disciplinary collaboration: finite-element model updating procedure for flutter analysis models

In the considered case study we aim to improve the flutter certification process for small aircraft by a closer analysis-experiment interaction, involving multiple distributed collaborating partners. The process is outlined in Figure 2. This case study is applied to the I-23 aircraft, which is a small reference aircraft within the CESAR project. The demonstrator is described in section 5.

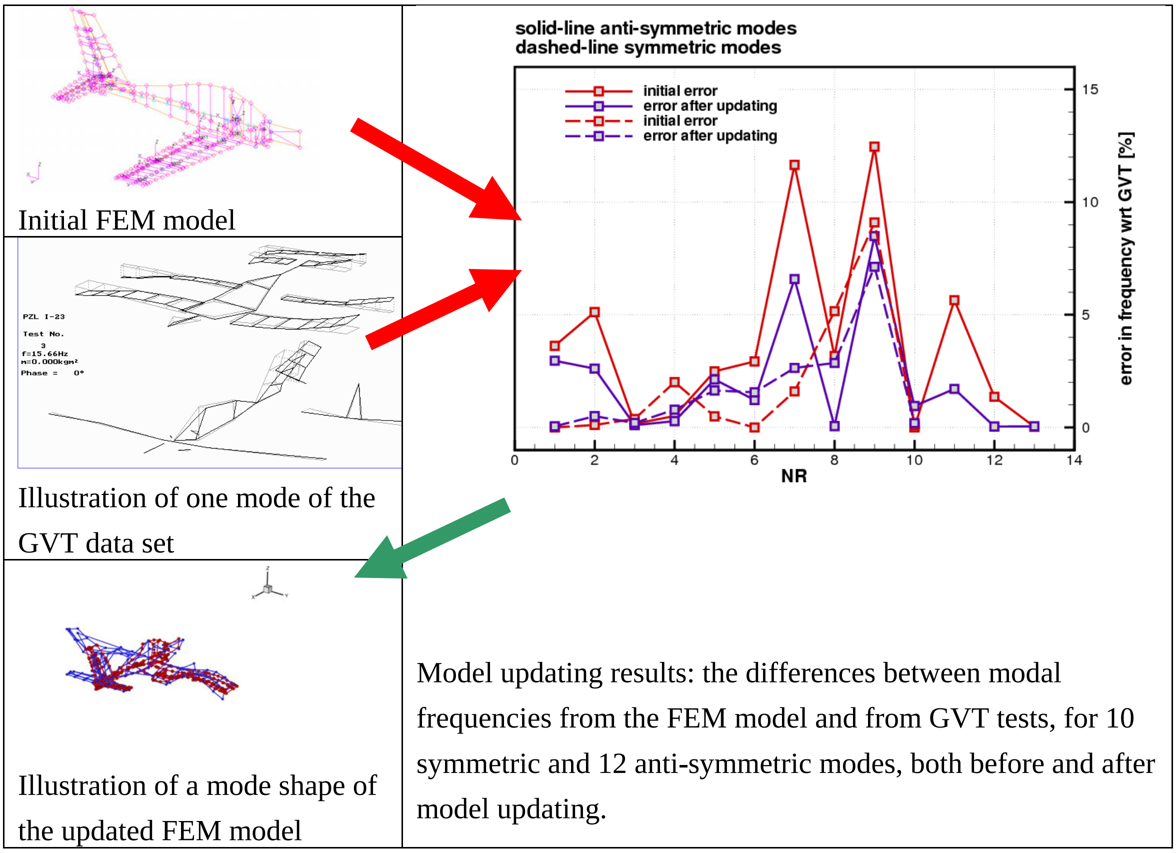

Figure 2. Illustration of the model updating process. The updated model has clearly lower frequency errors, i.e. better correspondence with the GVT test data and hence provides more realistic flutter analysis.

For this aircraft a Finite Element Method (FEM) model was implemented in the finite element software MSC Nastran, based on elastic beam elements and with about 550 nodes. This model is available at one partner, who intends to apply this model for flutter analyses. However, for these analyses it is important to have good model accuracy. This can be achieved by matching the model to experimental data that typically comes from so-called ground vibration tests (GVT). A set of these data for the I-23 aircraft is available at a second partner and consists of data from about 140 unidirectional displacement sensors for about 75 different vibration modes. The matching of the model with the experimental data, i.e. the actual model updating process, is operational at a third partner. This process can be deployed if the model and the experimental data are available, and then yields an updated model. The updated model is delivered back to the first partner, who can then proceed with the flutter analysis of the I-23 aircraft.

The approach followed in the model updating process is based on advanced model updating methods [3], typically developed for large FEM models (i.e. many degrees of freedom), and applied here to moderate/small FEM models (i.e. relatively few degrees of freedom). The I-23 aircraft model updating process as applied in this case study comprises the following items:

- Inter- and extrapolation of the measured modal displacements (directions, size/scaling) in the GVT data to the predicted modal displacements from the FEM modal analyses.
- Identification of the corresponding modes in the model prediction and the experimental data. This results in a table with mode numbers, which is used as an input in the actual model updating process.
- Under the assumption that the inertial properties of the I-23 aircraft model are reasonably accurate, the model parameters that are considered for updating are the stiffnesses. The three stiffness parameters (torsion about the beam axis and bending about the two perpendicular axes) for each beam element in the model are updated.
- The model response quantities that are currently used in the comparison with the GVT data are the modal frequencies. In addition also mode shape quantities based on so-called modal assurance criteria could be used, but have not been considered in the present study.
- The optimisation, i.e. the actual model updating of the model parameters (stiffnesses), is achieved by using the Nastran SOL200 optimisation solver.
- The resulting updated model has such stiffness values that the modal frequencies are consistent with the data from GVT experiments. This model can be then used for the flutter analyses.

The implementation of this model updating procedure is briefly described below.

3.1 Model updating procedure

The present model updating procedure follows the computational model updating procedures. Starting from an initial FEM model, the objective is to find the model parameters which improve the characteristics of the model to resemble the experimental data as closely as possible. It should be noted, however, that the exercise should be directed towards removing modelling inaccuracy and not only to produce a model with less relation to the physics of the aircraft. Moreover, the selected approach is to take advantage of the optimisation capability of

NASTRAN. The design optimisation module of NASTRAN is usually applied to minimise a certain design objective, for example weight, for prescribed parameters, for example element properties or even the geometry. The present approach uses the design optimisation module of NASTRAN to minimise the differences between the FEM model results and the experiment.

3.2 Updating through optimisation

To set up an optimisation process, an error function has to be defined which represents the differences between the analytical model and the experimental data. First, consider the vector or error in the natural frequency *f* as:

$$\{\varepsilon\} = \left\{ \frac{f_A - f_G}{f_G} \right\} \tag{1}$$

The subscripts *A* and *G* represent the analytical model and the GVT data, respectively. The error $\{\varepsilon\}$ is function of the selected design parameters, i.e. parameters which may be modified during the optimisation process. An optimisation process can be set up to minimise this error by defining the objective function to be the sum of squared error as:

$$O_\varepsilon = \{\varepsilon\}^T \{\varepsilon\} \tag{2}$$

The expressions given above are based on the implicit assumption that the errors are uncorrelated with each other and with the independent design parameters, and moreover have equal variance. As generally known, experimental data may contain inaccuracies. In most cases, the inaccuracy varies between modes. Therefore it is more appropriate to express the minimisation problem with a weighted-squared sum type of objective function, where the following scalar objective function is minimised:

$$O_T = \{\varepsilon\}^T [W_T] \{\varepsilon\} \tag{3}$$

The weighting factor represented by matrix $[W_T]$ can be specified differently for each mode to reflect the confidence in the test data.

It should be clear that a minimisation procedure using the aforementioned objective function O_T does not take into account any consequences on the magnitude of the parameter change from the initial value. In some cases, the starting value of the design parameters, i.e. the initial analytical model, could already be good. As long as the value of the error is reduced, any change in the parameters is always considered to be superior to the initial value, no matter what magnitude or sign. This situation could lead to a mathematical model which may not be representative to the physics of the aircraft. In such case, usage of the model beyond the optimisation range would likely to give unsatisfactory results. Therefore, the commonly used approach of limiting the parameter change is used. First define the change in the parameter value as:

$$\{\Delta p\} = \left\{ \frac{p - p_0}{p_0} \right\} \tag{4}$$

Additional weighted least square term to minimise the change of the parameter is added to objective function O_T to arrive at:

$$O = \{\varepsilon\}^T [W_T] \{\varepsilon\} + \{\Delta p\}^T [W_p] \{\Delta p\} \tag{5}$$

The weighting factor $[W_P]$ represents the confidence in the initial model. It should be set to a large value when confidence is high, and the other way around in the case of high uncertainty. The new term can also be seen as a regularisation term to the objective function which is very useful when the gradient of the original objective function $\partial O_T/\partial p$ is close to singular.

3.3 Implementation in NASTRAN

The implementation of the aforementioned optimisation procedure in NASTRAN is relatively straightforward. First, the design variables are selected and the side constraints are defined. The Young modulus is defined in the NASTRAN *bdf* file as a design variable, which is allowed to change from 99% up to 101% during the optimisation. The design variable is proportional to the element or material properties. In general it can be linear, quadratic, etc. To evaluate the objective function during the optimisation process, the characteristics of the modified model need be examined. This is done through the so-called design responses, which can be extracted per mode. Both design parameters and the design responses are used to define the objective function to be minimised, i.e. Equation (5).

For a design optimisation run, the SOL 200 module of NASTRAN is used. The optimisation process in NASTRAN uses an approximate model to accelerate the process, see Figure 3. The default optimiser, used in the present work, is gradient-based.

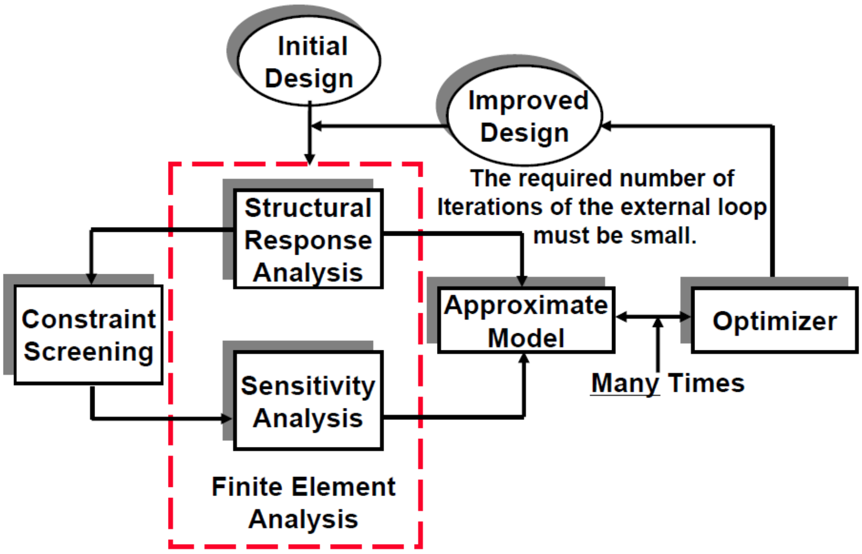

Figure 3 Schematic diagram of optimisation process implemented in NASTRAN

NASTRAN eigenvalue extraction during SOL 200 runs has a very useful feature called mode tracking. The computed modes during subsequent updates of parameters are ordered according to the initial numbering. This is done by using cross-orthogonality checks between the current and previous modes during design iterations. In this way the initial model can be used as a fixed reference.

4 A practical approach to distributed multi-partner collaboration

An important goal of the IDS is to facilitate collaboration among distributed multidisciplinary small-aircraft design engineering partners. Collaboration solutions have been demonstrated in EU projects such as FACE [4] and VIVACE [5], but are however mainly targeted towards large aircraft industries.

The collaboration solutions demand large investments from the partners involved, due to the potentially high tooling and licensing costs as well as the required change of culture. This change concerns convincing and enabling highly specialized engineers to change their modes of working and to use different "standard" skill tools as prescribed by the integrator. Large aircraft integrators and their supply chains usually can afford the investments, but the European small-aircraft industry cannot. In the IDS, a solution that requires minimum investments from the partners has been investigated. The solution comprises two technologies that contribute most significantly to effective collaboration: secure remote information sharing and distributed multi-partner job coordination. These technologies are described in the following subsections.

4.1 Secure remote information sharing

The European small-aircraft industrial partners tend to use their own engineering processes and skill tools to perform their parts of the collaborative jobs. As such, tool interoperability at data level is an issue, but tool sharing is not. The partners need to exchange information, including documents and data files, to accomplish a collaborative engineering job. Consequently, one of the cornerstones of the IDS is its support for efficient sharing of engineering information. The support consists of a central Data File Repository (DFR) that is hosted by one partner and that is accessible to the other partners over the internet via common, standard web technology. It provides the partners with a powerful web-based tool for secure remote sharing and exchange of engineering information with minimum investments.

The repository is realized using *Microsoft SharePoint* [6]. It is installed on a computer in a "demilitarised zone" of the NLR computer network, making it is accessible to the partners in a secure way. The repository hosts several data areas for the various activities in the CESAR project. The files in each data area are version-controlled and may be organized in a folder structure. Each file is uniquely identified by a web address, which allows easy reference in e-mail messages and web pages. Collaborating engineers can access the repository using a standard web browser as well as "standard" file managers such as Windows Explorer, to upload and download files.

To ensure secure information sharing, the repository provides authentication, authorisation, and encrypted data transfer. The authorization and authentication is based on the notions of users, groups and group memberships, which is controlled by user administrators. Users need to authenticate themselves when accessing the repository. Access to data is defined for each data area separately, and is based on user roles and permissions. For example, users from a Reader group may only read files without modifying and deleting the files. The data transfer between the user and the web site is encrypted through the use of Secure HTTP (HTTPS).

4.2 Distributed multi-partner job coordination

Another cornerstone of the IDS is its support for the coordination of distributed multi-partner collaborative engineering jobs. The coordination involves job decomposition, workflow execution, and results collection.

Execution of a collaborative engineering job starts with the decomposition of the job into tasks that can be performed by individual partners. The decomposition is specified in terms of a "workflow", which defines a scenario of the successive tasks to be performed by the various partners to reach the collaborative result. A workflow is represented in terms of a directed graph. The nodes represent tasks and data holders. The arrows represent data flows between the nodes. To master complex jobs, workflows may be decomposed into sub-workflows. The coordination next concerns the execution of the tasks by the partners and the exchange of information involved, as specified by the workflow. The partners involved are triggered successively to perform their part of the job and provide their results when finished. The outputs of the workflow are finally collected to constitute the final results of the engineering job.

Workflow management systems to support multi-partner job coordination exist, but usually require investments for software, training, integration of legacy tools, and changing the usual ways of working. The IDS aimed at a light-weight solution, with minimum investments and overhead for the engineers. It is based on the approach that one partner plays the role of "conductor". Like a conductor who is responsible for the performance of a composition from sheet music by skilled musicians forming an orchestra, this partner coordinates the job execution among the partners according to the workflow. The exchange of data is accomplished by the DFR as introduced in the previous subsection. The global set-up of the conductor workflow is depicted in Figure 4.

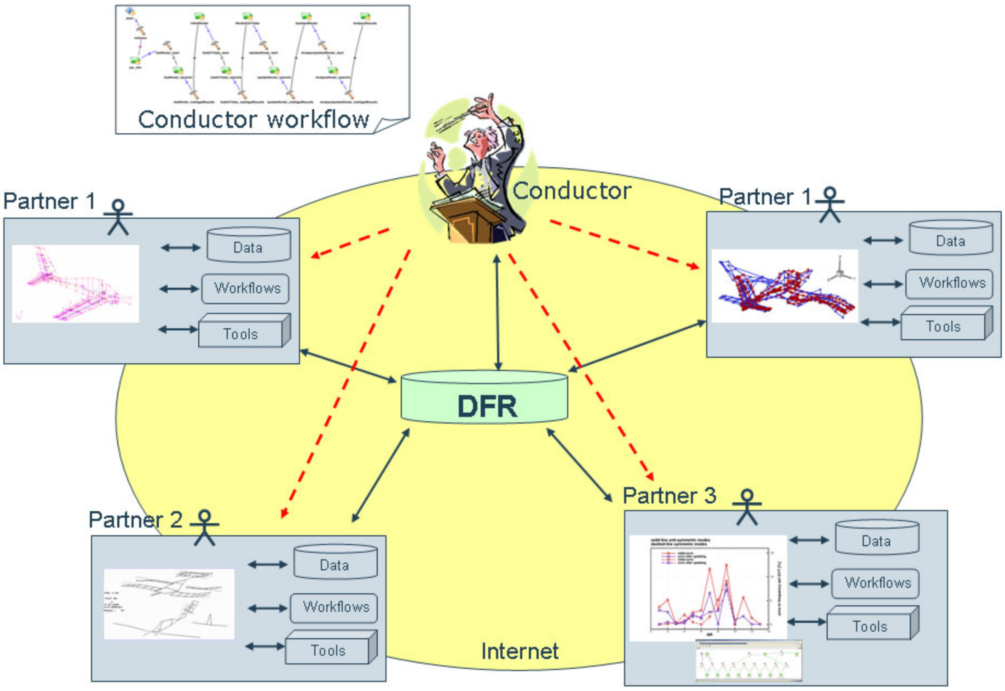

Figure 4. Global approach of the CESAR IDS support for multi-partner job coordination using Data File Repository (DFR) and the notion of Conductor workflow (see Figure 5)

Multi-partner engineering jobs usually involve complex workflows with loops (representing, for example, redesign and optimisation cycles). Hence, conducting a workflow by hand may be an error-prone and even boring activity. In addition, if some tasks are performed within few minutes or several days, the conducting may become a bottleneck and hamper the flow of tasks. To avoid this problem, a light-weight tool to support the conductor was introduced as part of the IDS: the Conductor-Workflow System (CWS).

This system is a workflow management tool that runs at the conductor's computer. The tool supports an "orchestrator" with the definition of a workflow. It provides the conductor with powerful means to coordinate the activities performed by the collaborating engineers at the various partners. It triggers the engineers to perform tasks by sending e-mail messages, which contain links to files and folders on the DFR. A triggered engineer uses the links to retrieve the applicable input, performs the task by using local tools, and finally uploads the results using the link designated as results placeholder. The CWS monitors the designated results placeholder to determine whether and when the partner finished his task. If all inputs are present for subsequent tasks in a workflow, the partner(s) involved are triggered.

The CWS automates most of the coordination activities, including administrative actions, partner triggering, and monitoring. The conductor may choose to initiate tasks by hand explicitly or to have the tasks start automatically as soon as the inputs involved are available. In the latter case, the conductor may monitor the progress of the workflow execution, and is occasionally prompted to answer questions and take decisions depending on the intermediate results.

The CWS is implemented using an NLR middleware toolkit for tool-chain automation [7] in combination with a small set of tools. The toolkit facilitates integration of legacy engineering skill tools, and supports the graphical composition and either interactive or batch execution of chains of tools. The toolkit itself is used in aerospace industry to support efficient definition and application of engineering processes and skill tools. It is recognized as a valuable tool to support reduction of development costs and time in aerospace engineering [8]. In our context, the toolkit is used for definition and execution of tool chains that implement conductor workflows. The conductor tool chain contains tools for accessing and monitoring the DFR and for sending e-mail messages to trigger the partners.

5 Description of the demonstrator

The combination of the technologies described in the previous section provides a practical and cost-effective multi-partner collaboration solution for the European small-aircraft industry. A demonstrator for the solution was built using the CWS and DFR. The CWS supports the definition and execution of the conductor workflow. The data holders in the conductor workflow serve mainly to control the execution of the tools. The actual engineering data involved with a job is passed among the partners via the DFR, in a specific folder that is created to hold the job’s input, intermediate, and output data. The links communicated with the partners in the context of the job designate files and folders in the job-specific folder.

The conductor workflow for the FEM model updating procedure for the flutter analysis models use case described in section 3 is depicted in Figure 5. It shows how the first partner initiates the job by requesting a model update for a particular aircraft. In response, the conductor starts the applicable conductor workflow. The conductor workflow first prompts the first partner to provide a model of the aircraft. Next, if the model is present, the second partner is prompted to provide the applicable experimental GVT data. Next, if this data is also present, the third partner is next prompted to perform the model updating procedure. Finally, if the updated model is present, the first partner is prompted to analyse the updated model.

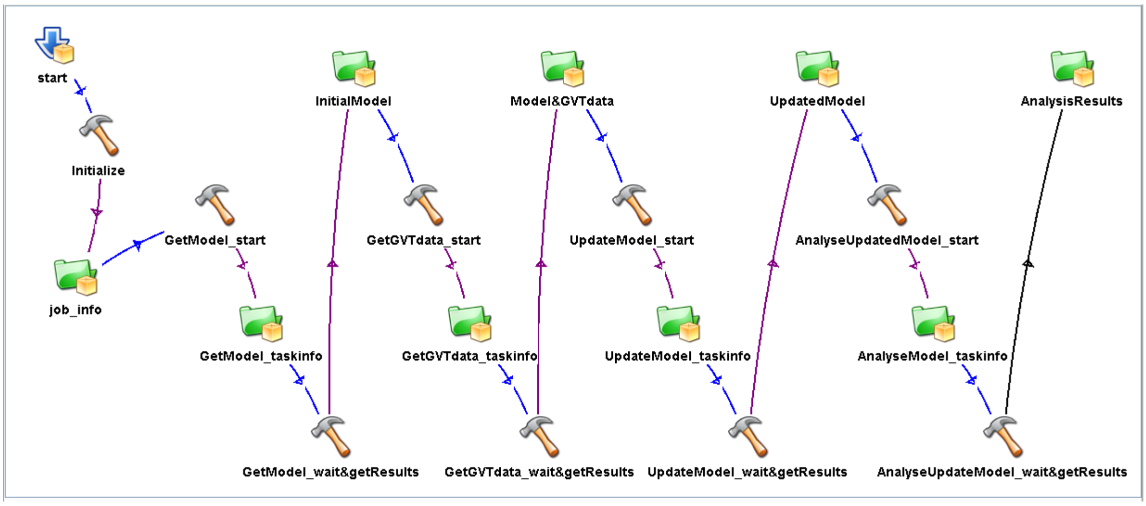

Figure 5. Conductor workflow for the finite element model updating procedure for flutter analysis models

An engineer starts a task by downloading the inputs from the job folder using the links in the e-mail message that triggered the task. Upon finishing the task, the engineer uploads the results to the job folder by drag-and-dropping the output files to a network folder that is opened in response to clicking the link of the designated output folder as specified in the triggering e-mail. Consequently, the overhead for an engineer is kept to a minimum, both in time, administrative actions, and the need to use specific software. Also, if the conductor workflow is executed automatically, the effort from the conductor is kept to a minimum.

The demonstrator presented here clearly supports the collaborative engineering process for FEM model updating in a multi-partner environment. The considered model updating process is illustrative for many other engineering processes that typically involve multiple analysis tools and data sets. These processes require strict definitions of data formats and of analysis steps in the process, in particular in the case that multiple partners play a role in this process. The benefits for such processes are achieved mainly in the efficiency of the collaboration of the various project partners in the areas of data-sharing and interactions among analyses chains, as demonstrated by the work presented in this report.

6 Conclusions and future work

In order to remain competitive, the European small-aircraft industry is challenged to reduce development cost and time of state-of-the-art products. The CESAR project investigated innovative improvements of the design processes of small-aircraft to enable the aerospace partners to collaborate closely to face the challenge. In this paper, we introduced the Integrated Design System (IDS) as a framework to support the multidisciplinary collaboration. The global set-up of the framework is based on integration of appropriate technologies using virtual collaborative environment concepts, data sharing and access under improved security and distributed computational concepts. This paper outlined how the practical application of the two state-of-the-art technologies positively support distributed partners to accomplish engineering jobs collaboratively, on a case study supporting the finite-element model updating process for flutter analysis models.

Experiences with the demonstrator show that the combination of existing technologies for information sharing and job coordination is a feasible solution for collaboration in the scene of the European small-aircraft industry. The technologies enable the partners to effectively play their role in the multi-partner engineering jobs as part of the aircraft design and development process. The technologies are available to the partners via common tools and usual ways of working, and as such do not require large investments on supporting tools and cultural changes.

Distributed integrated design capabilities amongst engineering teams working on various disciplines are affected by limitations on (commercial or proprietary) tools and increasing security policies at partner sides.
Future work will be directed towards extension and robustification of the supporting capabilities as a service-oriented environment. Additional functionalities provided by the combination of Conductor Workflow System and the Data-File Repository may be:

- Configuration management of engineering tools and data, for example, to support traceability (e.g. for certification purposes) and reuse of information and automated execution of conductor workflows.
- Improvements on iteration and parallelisation in conductor workflows.
- Automated generation of conductor workflows.

7 Acknowledgements

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