

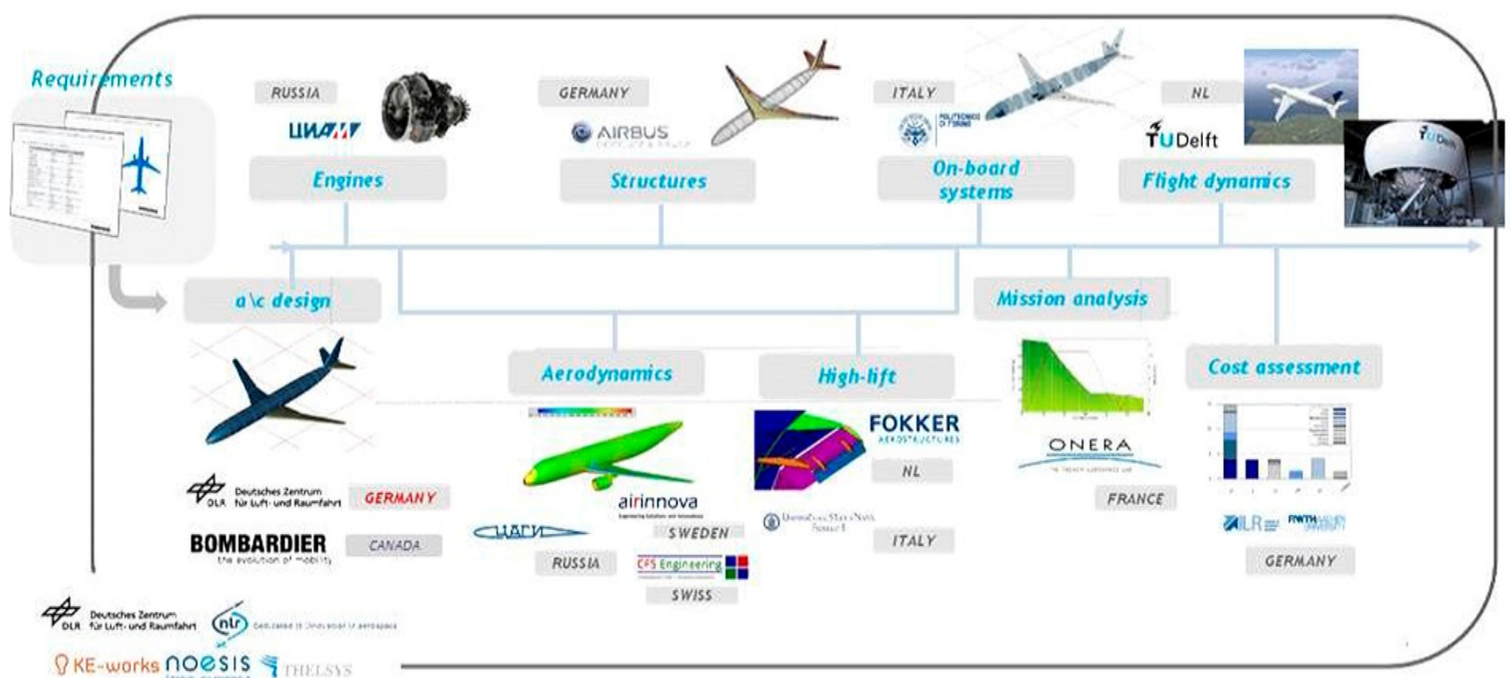


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NLR-TP-2017-249 | July 2017

# Collaborative Architecture supporting AGILE Design of Complex Aeronautics Products

CUSTOMER: European Commission



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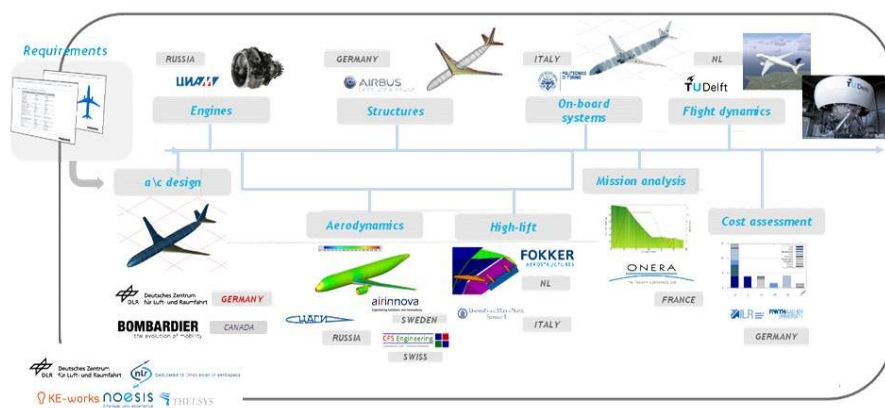
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# Collaborative Architecture supporting AGILE Design of Complex Aeronautics Products



## Problem area

The world is rapidly digitising. To keep up with the growing demand for more complex innovative products in shorter time and in higher volumes, industry digitises even more rapidly. The highly advanced aircraft industry more and more applies digital modelling, simulation and optimisation technology to be able to develop state-of-the-art aircraft more time and cost efficiently.

The aircraft manufacturer and its supply chain continuously innovate to manage the growing needs for and complexity of aircraft. Moreover, they need to meet the demands from airlines, air travellers and society, the regulations and constraints from authorities and airports, etc.

Efficient collaboration among the aircraft development supply chain is generally considered essential for developing aircraft. To this end, it is necessary to face the challenges, to master the complexity of today's aircraft development programmes, to spread risks and costs, and to join the power of the multiple experts and disciplines in aircraft development. The AGILE project aims at a significant reduction of aircraft development cost by enabling a more competitive supply chain for a reduced time to market of innovative aircraft products. The project develops innovative methods to support efficient collaborative design of conventional and future aircraft.

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### AUTHOR(S)

P.D. Ciampa  
E. Moerland  
D. Seider  
E.H. Baalbergen  
R. Lombardi  
R. D'Ippolito

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## Description of work

The AGILE project develops the next generation of aircraft Multidisciplinary Design and Optimization (MDO) processes, which target reduced development costs and time to market, leading to cost-effective and greener aircraft solutions. In order to enable and to accelerate the deployment of collaborative, large scale design and optimization frameworks, a novel methodology called the “AGILE Paradigm” has been formulated. A main element of the AGILE Paradigm is the Collaborative Architecture, which formalizes the collaborative process within the entire supply chain, and which defines how the multiple stakeholders interact with each other. NLR contributed to the AGILE Paradigm by providing methods and technology (Brics) to integrate local tool chains and competences into collaborative, cross-organisation MDO processes, thereby complying with the prevailing security constraints of the organisations involved.

## Results and conclusions

The AGILE Collaborative Architecture enables cross-organisational integration of distributed design competences. In the first year of the AGILE project, the AGILE Paradigm was successfully formulated, implemented, deployed among the AGILE project partners, and demonstrated. The paper presents the Collaborative Architecture concepts, the underlying requirements, and its main deployment elements. The use case described in this paper represents the first successful collaborative aircraft design process which is executed in a fully automated way, thereby integrating competences, tools and processes hosted at multiple organizations. The NLR technology has proven itself to enable cross-organisation workflow execution, and hence to be a crucial element of the AGILE Collaborative Platform.

## Applicability

The technologies comprised in the AGILE Collaborative Architecture implementation, including NLR’s cross-organisation workflow execution, may help the aircraft industrial partners, including the Dutch aircraft industry, to constitute a competitive supply chain.

### GENERAL NOTE

This report is based on a presentation held at the 18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, AIAA AVIATION Forum, Denver, Colorado, USA, June 5-9, 2017.

### NLR

Anthony Fokkerweg 2  
1059 CM Amsterdam

p ) +31 88 511 3113 f ) +31 88 511 3210  
e ) info@nlr.nl i ) www.nlr.nl



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**R. D'Ippolito**

DLR, German Aerospace Center, Germany

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NLR


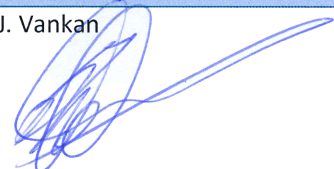

NOESIS Solutions N.V., Leuven, Belgium

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# A Collaborative Architecture supporting AGILE Design of Complex Aeronautics Products

Pier Davide Ciampa<sup>1</sup>, Erwin Moerland<sup>2</sup> and Doreen Seider<sup>3</sup>  
DLR, German Aerospace Center, Germany

Erik Baalbergen<sup>4</sup>  
NLR Netherlands Aerospace Centre, Amsterdam, the Netherlands

and

Riccardo Lombardi<sup>5</sup> and Roberto D'Ippolito<sup>6</sup>  
NOESIS Solutions N.V., Leuven, Belgium

The AGILE project is developing the next generation of aircraft Multidisciplinary Design and Optimization processes, which target significant reductions in aircraft development costs and time to market, leading to cost-effective and greener aircraft solutions. In order to enable and to accelerate the deployment of collaborative, large scale design and optimization frameworks, the “AGILE Paradigm”, a novel methodology, has been formulated during the project. The main elements composing the AGILE Paradigm are the *Knowledge Architecture (KA)*, and the *Collaborative Architecture (CA)*. The first formalizes the overall product development process in a multi-level structure. The latter formalizes the collaborative process within the entire supply chain, and defines how the multiple stakeholders interact with each other. This paper focuses on the Collaborative Architecture, which enables cross-organizational and cross-the-nation integration of distributed design competences of all the 19 project partners. The paper presents the Collaborative Architecture concepts, the underlying requirements, and the main CA deployment elements. Although the deployment of the CA is product independent, the implementation is presented for the AGILE reference use case, addressing the design and optimization of a transport aircraft.

## Nomenclature

<i>ADF</i>	=	AGILE Development Framework
<i>AGILE</i>	=	Aircraft 3 <sup>rd</sup> Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
<i>CA</i>	=	AGILE Collaborative Architecture
<i>CPACS</i>	=	Common Parametric Aircraft Configuration Schema
<i>KA</i>	=	AGILE Knowledge Architecture
<i>KBE</i>	=	Knowledge Based Engineering
<i>MDA</i>	=	Multidisciplinary Design Analysis
<i>MDO</i>	=	Multidisciplinary Design Optimization
<i>PIDO</i>	=	Process Integration and Design Optimization
<i>SOA</i>	=	Service Oriented Architecture

<sup>1</sup>Team lead MDO Group, Integrated Aircraft Design Dpt., DLR, Hamburg, [pier-davide.ciampa@dlr.de](mailto:pier-davide.ciampa@dlr.de).

<sup>2</sup>Team lead Collaborative Engineering Group, Integrated Aircraft Design Dpt., DLR, Hamburg, [erwin.moerland@dlr.de](mailto:erwin.moerland@dlr.de).

<sup>3</sup>Team lead Distributed Systems, Distributed Systems and Component Software, DLR, Cologne, [doreen.seider@dlr.de](mailto:doreen.seider@dlr.de).

<sup>4</sup>Senior Scientist, Collaborative Engineering & Systems Department, Aerospace Vehicles, Anthony Fokkerweg 2, 1059 CM Amsterdam, [Erik.Baalbergen@nlr.nl](mailto:Erik.Baalbergen@nlr.nl).

<sup>5</sup>Research Engineer, Research and Innovation Dpt., Gaston Geenslaan 11, B4, 3001 Leuven-Belgium, [riccardo.lombardi@noesisolution.com](mailto:riccardo.lombardi@noesisolution.com).

<sup>6</sup>Research and Innovation Manager, Research and Innovation Dpt., Gaston Geenslaan 11, B4, 3001 Leuven-Belgium, [roberto.dippolito@noesisolution.com](mailto:roberto.dippolito@noesisolution.com).

## I. Introduction

Current aircraft development programs are realized as collaborative and multi-organizational design processes. A major challenge hampering cost effective design processes is to realize a streamlined integration of multidisciplinary design competences within the so-called virtual enterprise. The challenge is even greater when the required design services are provided by heterogeneous teams of specialists that are distributed across different organizations and nations. Therefore, the development of a “more competitive supply chain” is the key-enabler to deliver innovative aircraft products in a time and cost efficient manner. It is therefore important to connect not only the product models and simulation capabilities between organizations, but also to combine the competences of the different experts and the creation of a collaborative environment that permits to accelerate the design process in order to obtain the best possible solution. However, the setup of such a complex collaborative design process is not straightforward. Collaboration among experts and the use of cross-organizational simulation capabilities are facing multiple challenges. *Efficient* collaboration between potentially competitive partners, in a dynamic IT environment comprising heterogeneous engineering environments and tools, with different levels of (company) security constraints, requires a step change in thinking, collaboration methods and tools.

Cross-organizational collaboration faces multiple challenges at several levels in order to become effective. Once the benefits of the collaboration have been identified and before the expert engineers start joining and streamlining their efforts, knowledge and tools, measures must be taken at the *organizational level*. Such measures include the establishment of trust among the organizations; the arrangement of compliancy with regulations (e.g., ITAR [1] and other export regulations at the national levels); the conclusion of contracts to define the costs and work distribution, responsibilities and communication lines; and agreements on the disclosure of information and knowledge. As example for these kind of measures at organizational level, the TSCP programme [2], which is supported by several large industries and government agencies, addresses the organizational aspects in the aerospace and defense area. In addition to this, measures to deal with the *typical ‘human’ aspects of collaboration* must be addressed. These aspects include resolving the ‘not invented here’ syndrome (i.e. proper understanding of meaning, validity, and (un-)certainty of outcomes of black-box calculations is needed); differences in culture, “language” and nomenclature; lack of common understanding of the context, overall work and process; disruptions in human communication; unawareness of each other’s competences; and introducing methods to include the required implicit knowledge behind tools in design processes. These aspects shall not be underestimated and certainly deserve attention before being able to collaborate efficiently.

Next to the organizational and ‘human’ level of collaboration, the *technical level* needs to be taken care of in multi-engineer collaboration. Collaborating at the technical level faces the engineers with issues such as agreement on, and joint set-up of models, execution of simulations, and management of results; interconnecting the generally heterogeneous working environments, operating systems, networks, ways of working, methods, tools, data sets and management and configuration procedures; and the sharing and exchange of technical data in commonly agreed formats. Several EU-funded projects, such as VIVACE [3], CESAR [4], CRESCENDO [5] and TOICA [6], have successfully investigated and developed methods to support efficient multi-engineer collaboration. However, the application of methods and cross-organizational scenarios still suffers from dynamic IT environments with more and more measures resulting from increasing self-protection and growing security constraints of the organizations involved. Despite the contracts and arrangements, collaborating engineers are still facing network restrictions, proxy servers, and firewalls that hamper setup and smooth execution of engineering simulations across organizational borders [7]. Finally, a collaboration system needs to account for the variety of legacy methods, processes and tools in place at the different organizations.

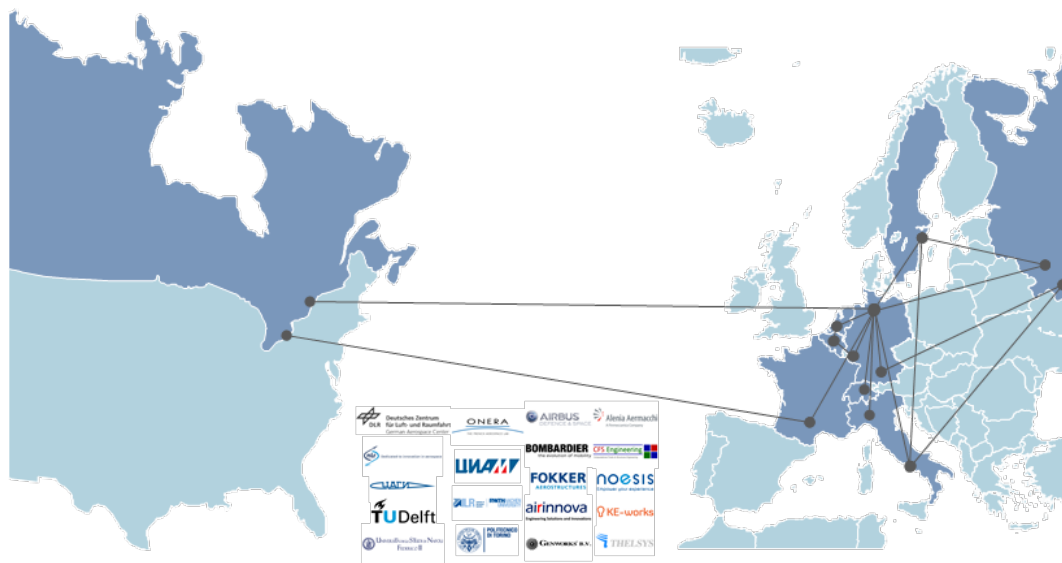
Many of the above mentioned collaborative development challenges are addressed in the AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) [8] EU funded H2020 project, coordinated by the German Aerospace Center (DLR). Although the main focus of the project is on the development and provision of solutions for the technical level of collaboration, the organizational and human levels are also taken into account.

Section 2 provides an overview of the AGILE project and introduces the overall AGILE Paradigm. Section 3 presents the AGILE Collaborative Architecture. Section 4 describes the implementation of the collaborative platform as an instance of the Collaborative Architecture, including its different elements, within the AGILE Consortium. Section 5 provides a demonstration of the deployed architecture for the design and optimization of the

AGILE reference use case. The final section presents conclusions as well as an outlook in the promising future of collaborative engineering.

## II. AGILE Project and the AGILE Paradigm

The AGILE project is developing the next generation of aircraft Multidisciplinary Design and Optimization processes that target significant reductions in aircraft development costs and time to market, leading to cost-effective and greener aircraft solutions. To cope with the challenges of collaborative product development, a team of 19 industry, research and academia partners from Europe, Canada and Russia have joined their efforts. The composition of the AGILE consortium, shown in Figure 1, reflects the heterogeneous structure characteristic for today's aircraft development teams and virtual supply chains: it includes airframe OEMs, suppliers, as well as organizations providing specialist design teams. Due to the diversity of partners, multiple collaborative scenarios are formulated and resolved during the project.

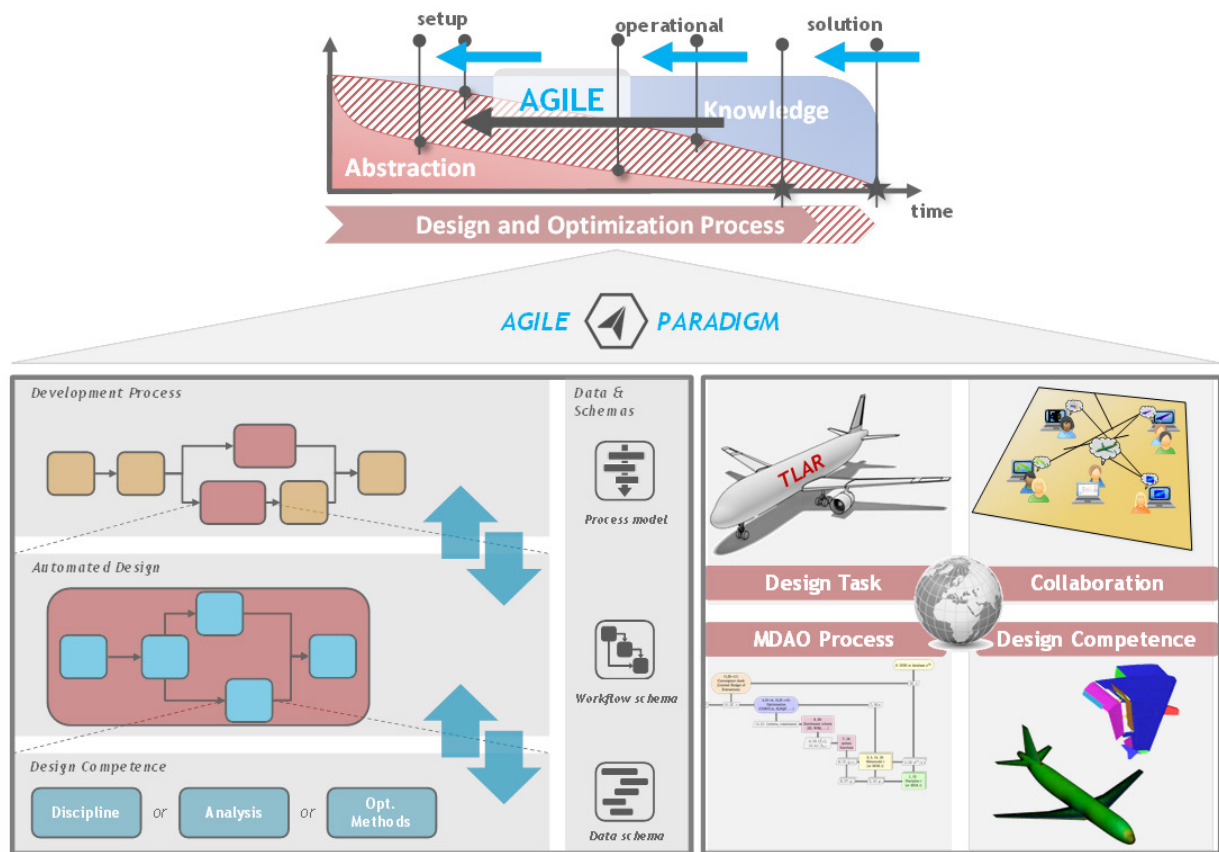


**Figure 1. Cross-organizational and cross-country integration of competences made possible by the collaborative architecture. The network represents the exchange of information within an AGILE project application, as described in section IV.**

To enable the third generation of MDO, whose challenges are presented in [9], the AGILE Consortium has formulated a novel design methodology, the so-called “AGILE Paradigm”, that supports the deployment of collaborative, large scale design and optimization frameworks, and that in particular (as shown in Figure 2) will:

- Accelerate the setup and the deployment of distributed, cross-organizational MDO processes
- Support the collaborative operation of design systems: integrate specialists and tools
- Exploit the potentials offered by the latest technologies in collaborative design and optimization

The overall methodology is introduced in [10]. The implementation of the AGILE Paradigm enables effective collaborative design and optimization of aircraft practiced by heterogeneous design teams, located multi-site, and with distributed expertise. The main conceptual elements constituting the AGILE Paradigm are schematically shown in Figure 2 and explained hereafter.



**Figure 2. AGILE Paradigm - conceptual elements.**

The main elements composing the AGILE Paradigm are the *Knowledge Architecture (KA)*, and the *Collaborative Architecture (CA)*. The first formalizes the overall product development process as a hierarchical layered-structured process. The latter formalizes the collaborative development process, and defines how the multiple stakeholders, acting within each layer of the development process, interface with each other within the entire supply chain. The Collaborative Architecture enables cross-organizational and cross-the-nation integration of distributed design competences of all project partners. The overall AGILE Paradigm is implemented in the so-called AGILE Development Framework (ADF), which defines the overall MDO platform developed in AGILE. The Collaborative Architecture defines the required collaboration elements which need to be deployed to enable effective collaboration within the ADF. The ADF is used for the Collaborative Development Process of aircraft or other complex systems, and can be used to support multiple development stages, such as feasibility studies, conceptual design and/or detailed design. An extensive description on AGILE development process is given in the companion paper [11], with focus on the AGILE Knowledge Architecture. The Collaborative Architecture is the main focus of the current paper, and more details are provided in the following sections.

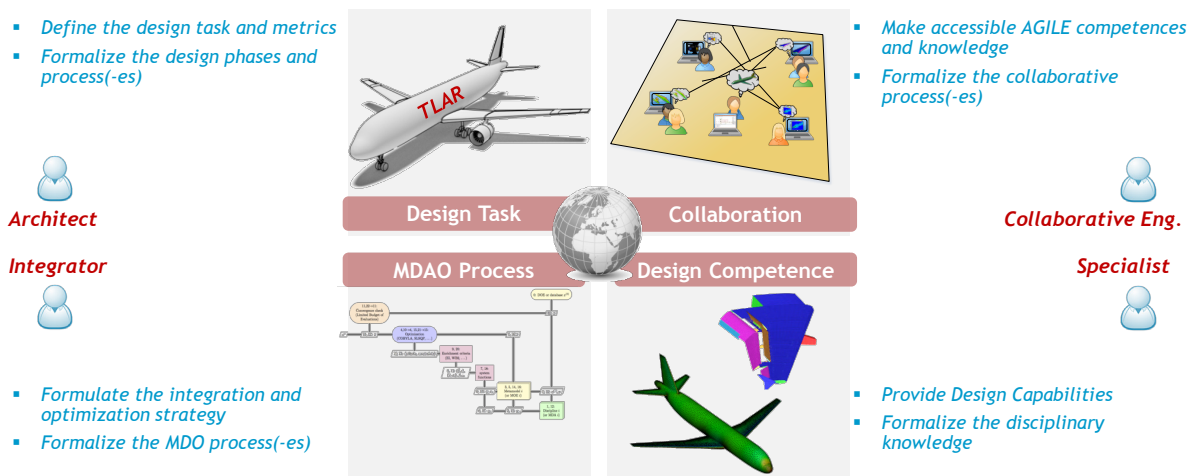
### III. AGILE Collaborative Architecture

Designs of state-of-the-art aircraft and aircraft components are the result of collaborative efforts of engineers from different disciplines and organizations, including the aircraft integrator and its supply chain. Apart from legal and contractual arrangements to enable organizations to collaborate on organizational level, technical arrangements are required to enable engineers on the workfloors of the organizations involved to collaborate in jointly performing design analyses. The collaborative architecture formulated in AGILE provides the means to connect simulation tools to the network in a service-oriented scenario. In addition to providing the network backbone for the design process, it also provides solutions for the cross-human and cross-organizational issues occurring in the design process. The current section describes the relations between the multiple stakeholders involved in the AGILE design and optimization task, and the IT aspects of the collaborative architecture. The AGILE development framework has been

put in place to facilitate the collaborative engineering activities. As such, the framework supports the overall target of the AGILE project to reduce the aircraft development time at the early stages of the design process, pronouncing the synergies between the heterogeneous disciplinary experts and the overall product architect, whilst addressing all the components of the supply chain network. The AGILE development framework is based on a system-wide approach of Service Oriented Architecture (SOA) in order to improve the integration of engineering services, within development workflows.

### A. Participative Agents in Collaborative MDO

The primary objective of the Collaborative Architecture is to enable streamlined and effective interactions among the distributed and heterogeneous participants, involved in the product development process. Therefore, in collaborative MDO tasks multiple types of participants can be identified, each performing a dedicated role, and operating within a specific step of the overall development. In AGILE, the main participative agents composing the Collaborative Architecture are illustrated in Figure 3.



**Figure 3. AGILE Collaborative Architecture – Participative Agents**

Design competences represent specific capabilities (such as a disciplinary simulation, or an optimization method), which can be integrated in a collaborative design and optimization process. The design competences provided by the partners are distributed across teams of experts located at multiple sites, each having their own IT infrastructure (network, simulation tools & capabilities). Providing simulation capabilities in the form of automatically executable engineering services provides the means to efficiently perform integrated design studies using distributed simulation workflows. It avoids the non-creative, repetitive, and error-prone manual data conversion steps, tool executions, and data exchange. During and after performing the design studies, the interpretation of the results on a disciplinary level and their influence on the overall aircraft design level requires the inclusion of the implicit knowledge of the specialists behind the services [12]. Therefore, a provided design competence consists of both a connection to a simulation tool within the projects' network to provide simulation capabilities of an explicit nature as well as the active inclusion of the implicit knowledge behind the tools. In the MDO Process, multiple individual simulation competences are integrated into a collaborative simulation workflow, composed by logically ordering the available simulation competence. The MDO strategy and architecture of the process are formulated by the integrator. Furthermore, multiple MDO processes can be setup, handling different phases of the development (e.g. conceptual, preliminary aircraft design phases), and multiple levels of details (e.g. full airframe optimization, component optimization). The architect is involved in the definition of the product's specifications, as well as in setting the boundary conditions of the design task, such as the available lead time and costs constrains. The development and monitoring of the design task is in close relation with the MDO process (or sub-processes) integrator(s). Therefore, the development process formulated by the architect includes automated and manual operations. As realized during the AGILE project, as well as in previous projects, such a complex system cannot be handled by a single workflow integrator alone. Hence, the collaboration among all the agents is enabled and facilitated by the collaborative engineer. Finally the AGILE development framework is developed to be used by the framework customer, which may interact during the operational phases, for instance to access the final or partial results, and to participate to the decision making process when required.



The main responsibilities of the main agents are listed in Table 1.

**Table 1 Agents of the AGILE framework**

#	Participative Agents	Responsibility
1	Customer	Customer and primary user of the framework. Responsible for defining the design task, top-level requirements, and available development lead-time. It includes the retrieval of results from the AGILE framework.
2	Architect	Responsible for specification of the design case in the AGILE framework, such as collecting the required competences, defining the design phases and the dimensionality of the design space to be explored.
3	Integrator	Responsible for the deployment of the design and optimization (sub-) processes, and for the management of such processes within the AGILE framework. IP protection is also administrated.
4	Competence specialist	Responsible for providing design competence within the framework, such as a simulation for a specific domain, or an optimization service. Specifications of the competences are managed in the AGILE development framework.
5	Collaborative engineer	Responsible for providing the integration within the framework, necessary to connect the various competences and making them accessible to the framework. It includes the secure integration of software apps in different networks.

## B. Service Oriented Architecture

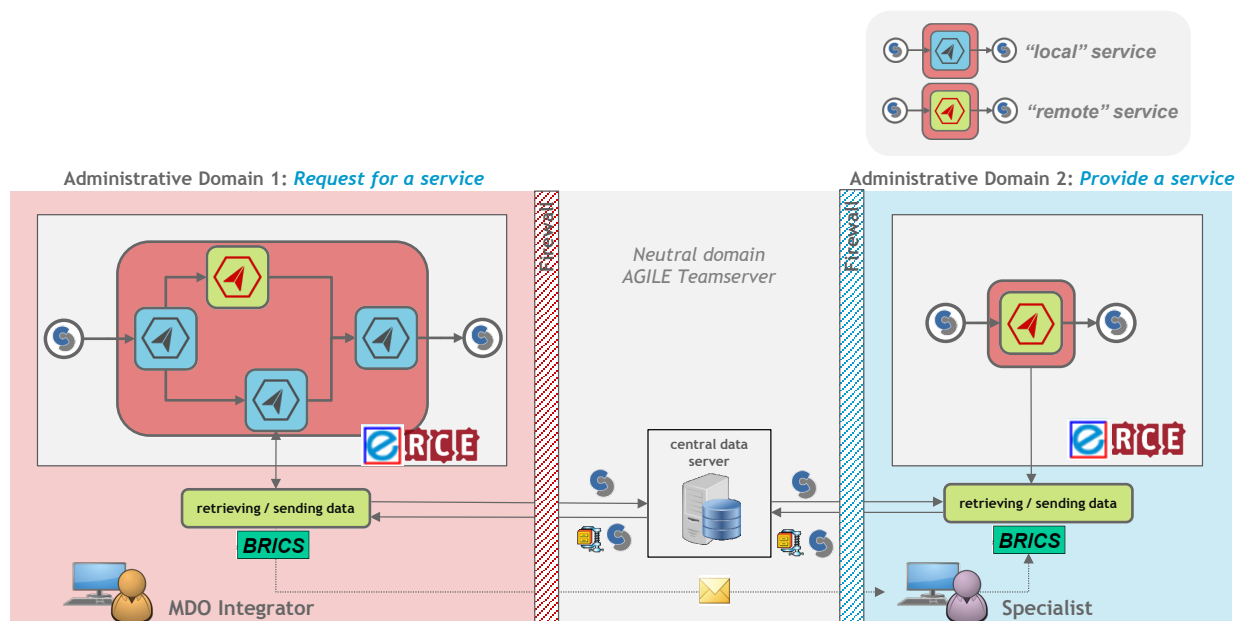
The concept of a Service-Oriented Architecture (SOA) originates from the field of software engineering, where it describes an architecture that is composed of different loosely-coupled components (applications) that offer services to other applications and users. A service is a (typically small) unit of functionality. For example this could be to perform a single analysis, serialize some data, or create a data plot. A system that is build according to this architectural pattern often also includes an orchestration module that handles the interactions between different services, and the orchestration of multiple services that have to be executed (for instance in a workflow). The main advantage of a service-oriented architecture is that it leads to a modular system. It enables service reuse, which limits the amount of work that has to be performed when a system needs to be modified or when a new system has to be build. Recently, efforts have been made to translate this concept of SOA to the engineering world, especially in engineering IT frameworks [1]. In the AGILE SOA, two main basic scenarios are formulated within an MDO process:

- Requesting for a Service – MDO process integrator’s perspective
- Providing a Service – Specialist design competence provider’s perspective

The SOA nature of the AGILE collaborative architecture is schematically shown in Figure 4. The MDO process integrator defines and deploys a design and optimization workflow in the administrative domain 1, defining a certain organization. In such a MDO process, the integrator requests for multiple simulation services, located within the administrative domain 1 and/or located in external administrative domains if provided by other organizations. Each arrow connection from one service to another resembles the exchange of all required data containing the input for the service to start execution. Once a service’s execution is finished, its results are provided to the next service in the workflow, thereby constantly enriching the data exchanged. Beside three *local services*, indicated by the blue simulation tool blocks, a *remote service* of one of the partners in the network is included in the workflow. Indicated in green, this remote tool resembles an engineering capability within administrative domain 2. The aforementioned input and enriched output data needs to cross administrative domains when a remote design competence is included in the workflow. To allow for this data to be securely exchanged, a neutral domain is established, consisting of a central data server for the instantaneous exchange of data. When the remote service is triggered, the required input data is uploaded to the central data server.

Simultaneously, the owner of the service is notified that one or more runs of his/her service are requested. By providing the option to allow, postpone or disallow the tool execution, the owner retains full control over the tool

provided as a service. When allowing execution, data is automatically pulled from the central data server and provided to the tool under consideration. After execution, the enhanced results are fed back to the central data server and automatically retrieved within administrative domain 1. When a design of experiments or optimization is performed by the simulation workflow integrator, the tool owner can allow multiple executions of the owned service at once. The moment the design study is finished, computation allowance is automatically closed down. The specialist providing a service to the collaborative network needs to retain complete control over the availability, versioning and execution of his/her simulation tool. Therefore, a major feature of the collaborative architecture is that simulation tools connected to the network remain on the dedicated servers within the administrative domain of the individual partners. Furthermore a mechanism is included that allows administrators of the simulation tools to authorize a request for tool execution. The described methodology of ‘gluing’ multiple administrative into a single simulation workflow using the neutral domain is scalable up to very complex workflows including a large multitude of tools in different administrative domains. Finally, multiple automated design processes can be combined with human tasks in a *hybrid framework*, within the execution of the overall AGILE development process.



**Figure 4. AGILE Collaborative Architecture. Service oriented scenario enabling multi-site, cross-organizational development processes**

### C. Requirements of the AGILE Collaborative Architecture

To develop the AGILE development framework, a large number of requirements were identified by the AGILE Consortium. In this section, only the main requirements addressing the deployment of the Collaborative Architecture are presented. The requirements are clustered in four main domains:

- Requirements regarding the management and use of services
- Requirements regarding the flexible exchange of tools
- Requirements regarding the use of engineering knowledge and collaboration
- Requirements regarding the infrastructure

The requirements in this document are presented according to the MoSCoW classification [13]. In this classification, the following four levels of requirements are distinguished:

- **Must** - Describes a requirement that must be satisfied in the final solution for the solution to be considered a success.

- **Should** - Represents a high-priority item that should be included in the solution if it is possible. This is often a critical requirement but one which can be satisfied in other ways if strictly necessary.
- **Could** - Describes a requirement which is considered desirable but not necessary. This will be included if time and resources permit.
- **Won't** - Represents a requirement that stakeholders have agreed will not be implemented in a given release, but may be considered for the future.

#### ***Requirements regarding the management and use of services***

In view of the AGILE integrated approach, the integration of processes needs (e.g. in terms of security and trust of sources) an appropriate IT infrastructure. In these terms, cross organizational service-oriented collaborations have been proven themselves in many major sectors and companies that are adopting the technologies in real-world pilot applications within their businesses. Furthermore, workflow technology plays an important role within distributed infrastructures. It provides the enabling technology for defining and executing data and compute intensive workflows across organizational boundaries in support of distributed business collaborations. A workflow notation provides a natural way of describing the execution order of tasks (work units) and the dependencies between them. Informally, a workflow is an abstract description of the steps required for executing a particular real-world process, and the flow of information between them. Typically, workflows are authored through a visual programming interface where users can drag and drop icons representing the task nodes and connect them together. The utilization of distributed technologies, combining attitudes of service orientation (including definition of trust among service providers and consumers), distributed computational capabilities and workflows (using knowledge oriented approach) is a key enabler for the success of the design and validation activities of AGILE. As a consequence, system interoperability and information integration are key issues for collaboration and multidisciplinary optimization.

Main AGILE framework requirements identified in this domain are:

- The AGILE framework **must** facilitate a maintainable and extendable set of engineering services.
- It **must** be possible to execute the different tools used in the AGILE framework both from at least one of the workflow managers and individually.
- All tools **must** provide a point of contact in case additional information regarding the tool usage is required.
- The AGILE framework **should** support versioning, i.e. it must allow the end user to decide with which version of the tool a workflow should be executed.
- In the case of execution from a workflow manager, no human interaction **should** be required for the execution of the tool.
- Tools that are used in the framework **should** be tested using a predefined data set.

#### ***Requirements regarding the flexible exchange of tools***

Aircraft development programmes, similarly to engineering design programmes in other disciplines, include the traditional Conceptual, Preliminary, and Detailed Design phases. Each aircraft design phase has different design objectives and deliverables, employs design teams with substantially different skill sets, and executes design processes that involve significantly different lead times and levels of detail. In light of this, it is clear that a multilevel MDO capability is required to enhance fidelity and efficiency at the various phases of the development process. In other words, the MDO framework must support flexible exchange of different fidelity level tools, based on the current needs of the MDO team. This need is increased even more by the present tendency in industry to have loose boundaries between the classic phases mentioned in the beginning of this section.

Main AGILE framework requirements identified in this domain are:

- Different services that can be used for the same analysis in the AGILE framework **could** have a standardized interface, to facilitate easy exchange of these tools.
- The integration framework **must** support different fidelity level tools per discipline to support different phases in the MDO cycle (conceptual, preliminary and detail design).
- The framework **must** be able to alternate between the execution of analysis modules and surrogate models.



- When exchanging analysis modules, the framework **should** support retaining the coherency of phenomena analyzed and their model representation.

#### ***Requirements regarding the use of engineering knowledge and collaboration***

Cross-organizational collaboration among engineers seems obvious but certainly is not. Partner-specific security constraints and legal and contractual arrangements that are made among the collaborating partners often lead to complications for the engineers who need to collaborate. State-of-the-art aircraft and components design requires engineers collaborating on a higher level than just communicating by phone, video conference systems, e-mail or file-transfer tools. Preferably, the engineers play their roles in collaborative cross-organization business and engineering workflows, with clearly defined responsibilities and interfaces among their activities. The AGILE framework must cater for the definition of collaborative workflows, with clear and agreed-upon interfaces among the constituents. Such workflows ideally run seamlessly across organizational boundaries, thereby flexibly orchestrating the distributed activities and exchanging the data items smoothly between the activities and tools that run at the various different organizations. However, security constraints and derived measures oftentimes hamper the seamless execution of cross-organizational workflows. As a result, the collaborating engineers commonly have to deal with barriers such as firewalls, proxy servers, and use of specific VPN connections, which mainly serve to protect the networks, assets, and intellectual properties of the individual organizations. The AGILE framework is supposed to facilitate smooth workflow execution across organizational boundaries, thereby enabling orchestration and data exchange on the one hand while complying with the security constraints and intellectual property preservation of the organizations involved on the other hand.

Main AGILE framework requirements identified in this domain are:

- The framework **should** provide an optimization system comprising numerical measures and engineers in a single process for collaborative MDO
- The framework **must** support collaboration among different experts from various disciplines and heterogeneous tools for the generation and interpretation of results, as well as decision making.
- The framework **must** support collaboration among distributed MDO teams (i.e. with members in different geographical locations and different enterprises).
- The framework tools or additional tools within the framework **must** support proper visualization (real-time if possible) of data in order to support collaborative design decisions.
- The framework **must** support the execution of collaborative workflows across organizations thereby minimizing the impact or visibility of security barriers for the engineers involved.
- The framework **should** support definition and enforcement of responsibilities.
- The framework **must** support multi-site collaboration capabilities, data and tool accessibility, definition and smooth execution of collaborative multi-partner workflows.
- The framework **should** support secure locations and control of access rights to protect data integrity, intellectual property rights, licenses, NDAs, patents, trademarks, and security.
- The framework **must** obey the security constraints of the involved partners.
- The framework **must** support the security rules of the AGILE project.
- The framework **must** enable a collaboration partners to control access to and use of its own resources that are involved in collaborative actions/workflows.

#### ***Requirements regarding the infrastructure***

The ability to run collaborative workflows that connect experts and tools across computer, department and organization borders requires the possibility to connect people and IT resources among the computers, departments and organizations involved in the workflow. Security constraints may hamper straightforward seamless execution of workflows. For example, firewall settings may intentionally prohibit the automated or even human-controlled exchange of files between engineers working at different organizations, either via mail or a data server. The framework will provide capabilities that support smooth execution of workflows while complying with the security constraints. These capabilities however require some minimum functionality of the underlying IT infrastructure, which comprises the IT infrastructures of the collaborating partners as well as the network connections among the partners and the network capabilities and settings of the respective partners. If a partner does not allow any network traffic at all (incl. e-mail messages with attachments), it may be impossible for the partner to participate in a collaborative workflow, unless of course the exchange of data files via a USB key is allowed.

Main AGILE framework requirements identified in this domain are:

- The IT infrastructure of the framework **must** support collaboration and connectivity among MDO teams in different geographical locations and different enterprises.
- The IT infrastructure of the MDO framework **must** support the secure execution of cross-organization MDO workflows.
- The IT infrastructure of each organization participating in the collaborative MDO studies **must** provide sufficient connectivity to support the organization's IT infrastructure being part of the IT infrastructure of the MDO framework.
- The IT infrastructure **must** support secure exchange of data and data files to enable engineers and tools at different locations and in different network segments to exchange data, to protect data from unauthorized access.
- The IT infrastructure **must** support secure storage and access-control mechanisms to protect data integrity and security during storage.
- The IT infrastructure **must** support notifications being sent to and being received by humans.
- The IT infrastructure **must** support automated as well as human-initiated execution of tools and workflows, initiated from within as well as outside an organization.

#### IV. Deployment of the AGILE Collaborative Architecture

The collaborative architecture described in the previous section is a general representation that includes all the main elements that need to be implemented. In the AGILE project, the deployment of the Collaborative Architecture has been made using multiple technical solutions available within the AGILE Consortium. This section describes the technical solutions enabling the effective usage the collaborative architecture.

##### A. Deployment Elements

To enable the deployment of the AGILE SOA-based Collaborative Architecture, the following elements are necessary.

###### *Product data model Schema*

The application of a common language for exchanging information can drastically reduce the number of interfaces between the multitudes of services to be created, as indicated in Figure 5. The adoption of a common schema guiding the data exchange interfaces between design competences represents a main collaboration enabler by facilitating the overall product description within a network of heterogeneous competences. The definition of such a commonly accepted schema, feeding multiple abstractions of a product, presents a large challenge in itself.

In AGILE, the Common Parametric Aircraft Configuration Scheme (CPACS) [14] has been chosen to exchange product and tool specific information across the provided services. The data model is used to extract the input for the multiple design competences as well as to provide the output from the design competences. Although each design competence may provide additional data, in proprietary formats or other standards, the exchange between services is only via CPACS.



**Figure 5. Reduction of the amount of interfaces between engineering services by adopting a common data format**

### ***Process Integration and Design Optimization***

In an MDO task, the available design competences are integrated and orchestrated in a well-defined design and optimization process, which preferably can be automated. The process may be composed by multiple sub-processes, and may represent a design exploration (or optimization) study. These processes, can be configured, deployed and executed by making use of PIDO (Process Integration and Design Optimization) environments available at the different process integration sites. Typically, the architecture selected for the sub-processes provided by individual organizations reflects the organizations' structure and legacy processes. Therefore, the AGILE Collaborative Architecture shall enable the integration of multiple sub-processes, available at the partners' sites, without affecting the core of the legacy processes already available.

In AGILE multiple PIDO environments are available. One integration environment used in AGILE is the "Remote Component Environment" (RCE) [15], developed by DLR. RCE allows for interaction with the available engineering services within the network and to couple these in structured multidisciplinary simulation workflows. It provides a workspace for interaction among involved engineers as well as components for the management and splitting/merging of central data sets. NOESIS provides an alternative/complementary collaborative framework by means of Optimus [16], a process integration and optimization environment in which users can analyze and explore the design space and gain the critical insights of the dynamics of a virtual design problem. The implementation of the design processes in multiple PIDOs enables the formulation of a collaborative architecture that is completely flexible and software independent.

### ***Cross-organization interconnections among PIDO environments***

In a multi-partner collaborative MDO team, the available design competences are typically distributed among the partners. Consequently, the design and optimization process is a collaborative process that spans the PIDO environments available at the different process integration sites. Establishing a multi-partner collaborative architecture comprising the multiple PIDO environments requires cross-organization interconnections to be established among the PIDO environments. The interconnections must cater for orchestration of the distributed process and exchange of the relevant data, both across organizational borders. The orchestration involves the triggering of, and synchronization with remote sub-processes. The data exchanges include the feeding of input data to remote sub-processes and the receipt of result data from remote sub-processes. The interconnections must ensure that the data is exchanged in a secure way among the partners. The interconnections also have to comply with the security constraints and mechanisms of the partner organizations.

The interconnection mechanism available in AGILE is Brics [17], developed by NLR. Brics provides technology for interconnecting PIDO environments and for defining and streamlining workflows that cross organizational borders, while complying with the security constraints and dealing with the security measurements of the collaborating partners. Brics comprises protocols and middleware that facilitate remote execution of sub-processes from within a process, independent from the local PIDO environment (i.e., workflow manager) being used. Brics is based on a 'single-task' protocol that arranges the execution and data flow between an orchestrating ("master") process in one organization and a remote ("slave") sub-process in another organization under control of a specialist who is notified to start the sub-processes. To cater for iterations, Brics supports the notion of a 'multi-task' protocol, enabling a remote specialist to easily deal with series of similar sub-processes. Brics also supports easy experimentation with different set-ups of collaborative scenarios to support the Design Campaigns and configuration of services involved. Its nonintrusive character facilitates easy integration with existing COTS as well as in-house developed tools and solutions. It enables the AGILE partners to experience collaboration in a flexible and agile way even in early stages of collaboration and of development of collaborative scenarios.

Brics functionalities have been embedded by the PIDO providers using easy-to-use and modular interfaces in order to allow their inclusion in the workflows with minimal efforts and without need of programming skills. These building blocks are front-ends that expose to the user the basic information that Brics needs to operate. The AGILE integrator is only required to specify the files that will be transferred (usually, but not limited to, a single CPACS file), the name of the tool and the email address of the remote specialist. The specialists are notified through an e-mail message of the pending task, whose name and identification number are the only data that he has to be aware of to access the inputs.

The capacities of Brics have been separated into 3 components, each having specific functions:

- TaskCreator, used by the Integrator to connect the MDA with a discipline. Will pause the execution after the data upload, until the results of the required analysis has been received.
- Receiver, used by the specialist to retrieve and unpack the inputs from the remote server.
- Sender, used by the specialist to upload its results.

The TaskCreator effectively takes the place of the design competence to be requested, that is virtually replaced with a blackbox, preserving all the pre-existing links, execution sequence and variables connections. The Receiver and Sender interfaces task is to wrap the specialist tool by placing themselves at the very start and end of the execution chain. For CPACS-compatible tools, the integration is almost effortless with the received file that simply replace the local one. RCE and Optimus interfaces, although exteriorly different due to the characteristics of the respective PIDO environments, are built upon the same Brics functionalities and the exchanged tasks are fully compatible, thus preserving (and thanks to) Brics neutrality.

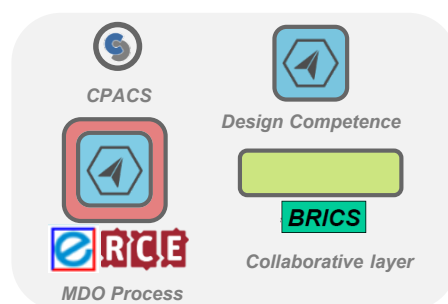
#### ***Neutral Data exchange Domain***

Within a design and optimization process, data needs to be exchanged among the distributed design competences. In AGILE, data exchanges among competences take place in terms of CPACS file exchanges, as explained in the section ‘Product data model Schema’. The file exchanges on behalf of the cross-organization collaborative design and optimization processes take place under control of the chosen technology for cross-organization interconnections among PIDO environments (Brics), which with respect to data security relies on underlying data exchange and storage security levels and mechanisms.

In the AGILE project context , a dedicated Microsoft SharePoint server – henceforth called the AGILE Teamsserver – has been set up to serve as data server for the exchange of data of the collaborative workflows in the various AGILE Design Campaigns. The communication between the design competences hosted at the partners’ administrative domains and the AGILE Teamsserver, is available via and under control from Brics. Brics relies on and uses the authentication and access-control mechanisms of the AGILE Teamsserver, as well as its access through HTTPS, to ensure the security constraints applicable to the data being exchanged among the partners. The configuration of the communication channel is triggered directly via the Brics plug-in developed in the PIDO environments RCE and Optimus.

#### **B. Deployment Steps**

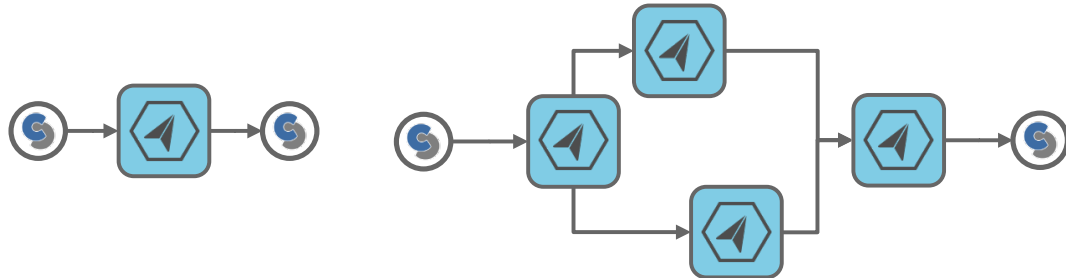
The AGILE MDO Collaborative Architecture is developed to enable accessibility to the engineering services provided by multiple Organizations, and composing a collaborative and distributed design and optimization process. In order to deploy the Collaborative Architecture, whose main elements are identified in Figure 6, the required deployment steps are described and illustrated in Figure 7 until Figure 9.



**Figure 6. Collaborative Architecture elements**

**Step 1: CPACS compliance**

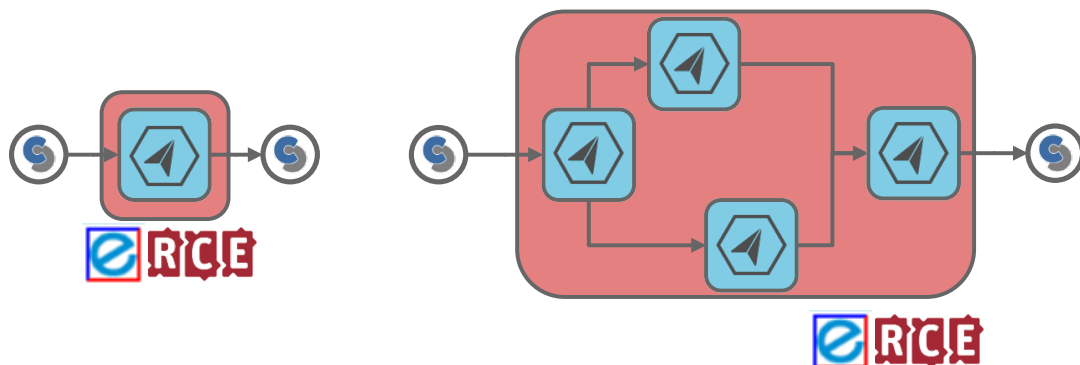
As a prerequisite, the “design competences” that are exposed as engineering services are required to be CPACS compatible. A design competence may be a single tool (or even tightly combining multiple tools) using CPACS as input and output of the requested analysis.



**Figure 7. Step 1 - Design Competences CPACS compatible. Single simulation tool, or multiple connected simulation tools**

**Step 2: PIDO Integration**

Next, the design competences must be exposed as design processes deployed into a single simulation framework - Optimus or RCE. The provided simulation workflow may integrate a single tool, or multiple distributed tools within the same administrative domain, and can be exposed as a single service.



**Figure 8. Step 2 - Multiple design competences are deployed as simulation workflows into PIDO environments Optimus or RCE. The workflow may consist of a single tool, or multiple independent tools arranged into a design process.**

**Step 3: Provide Accessibility**

In this step, the connectivity between design processes hosted in different administrative domains is provided via the Brics framework interface. The Brics layer provides orchestration of, and allows transferring input/output files between design competences hosted at different partners' administrative domains, which need to be accessible within the same design process.

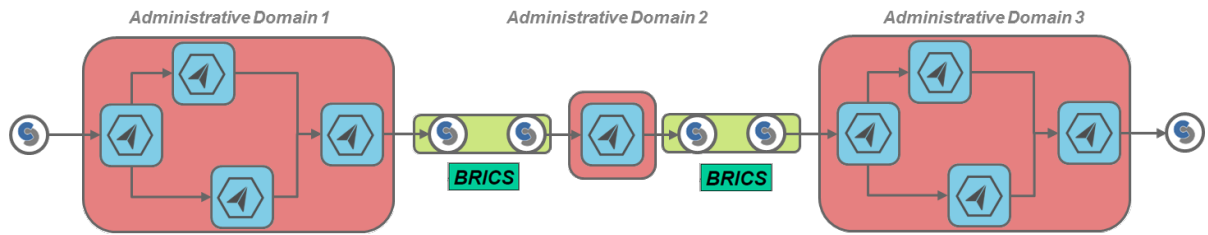


Figure 9. Step 3 - The design process is composed by multiple design competences, available in multiple administrative domains.

### V. Demonstrator - AGILE Design Campaign 1

The Collaborative Architecture, including its elements and steps described above, is illustrated by its deployment in the context of the first executed AGILE design campaign.

#### A. AGILE Design Campaign 1 – Scenario

The Design Campaign 1 (DC-1) is the first use case in the project that has been formulated and collaboratively solved by the AGILE team. This case consists of the design and optimization task for a large regional jet. Starting from the specification of the Top Level Aircraft Requirements (TLAR) provided by the aircraft manufacturer, an Overall Aircraft Design (OAD) task targeting conceptual and preliminary development stages was implemented in DC-1. The implementation resulted into a Multidisciplinary Design Analysis (MDA) system, operated for obtaining the solution of a Multidisciplinary Design and Optimization (MDO) problem. Figure 10 shows a representation of the DC-1 distributed MDO process. The figure indicates the domains of the specialists’ competences integrated into the process, the location where such simulation competences are hosted, and the specific partners providing such a competence within their IT networks.

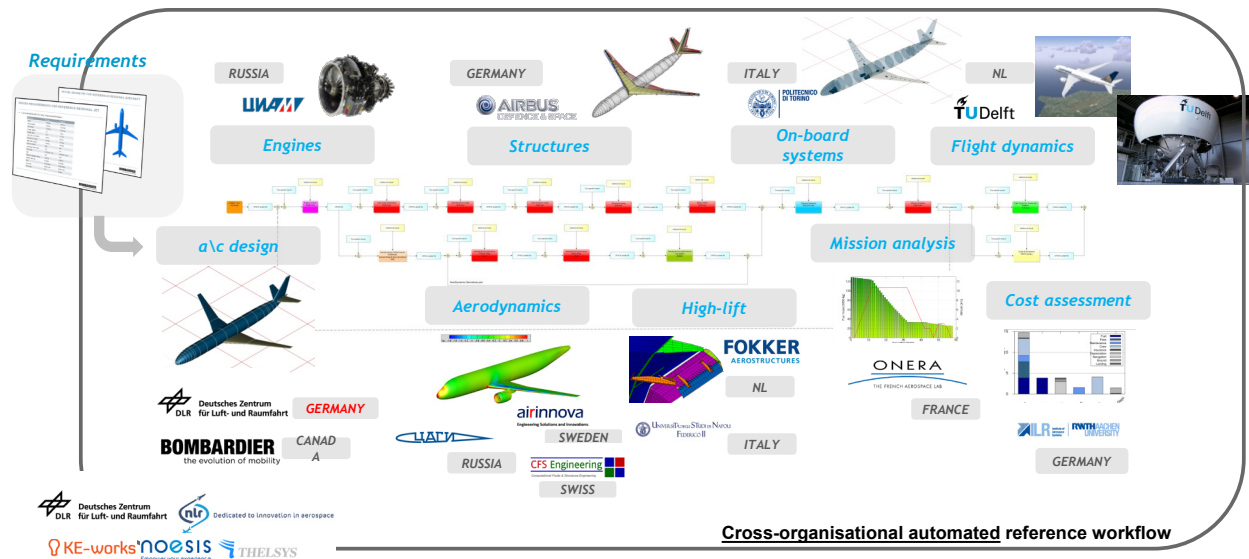


Figure 10. AGILE Collaborative design process: individual competences are distributed multi-site, and hosted at the different partner’s networks.



## B. AGILE Design Campaign 1 - Implementation

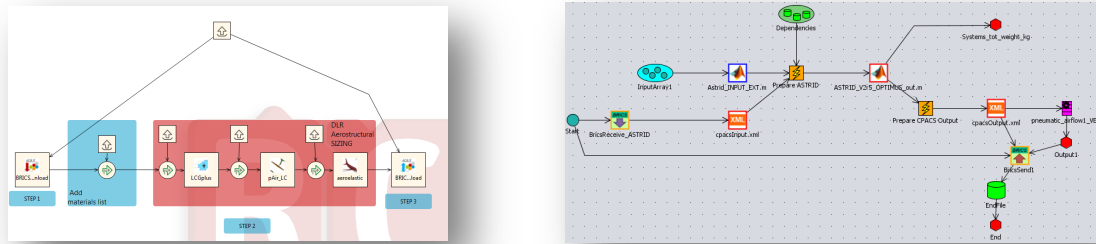
The pool of simulation tools available in the consortium includes software targeting the overall aircraft synthesis at the conceptual design stages, and disciplinary simulation capabilities with multiple levels of complexity and details. The disciplinary simulation capabilities include, among others, aerodynamics and structural solvers, propulsion and on-board systems design tools, and flight dynamics simulations capabilities. It should be stressed that not only the tools are provided but also the competence and experience of the partners executing the tools. This includes the possibility from the integrators and specialists to inspect the numerical results delivered during the execution of the design case, and collaboratively contribute to the decision making process. Therefore, the framework allows the accessibility to the intermediate results, and communication platforms were setup to enable regular teleconferences. Table 2 includes the list of the design competences that have been made CPACS compatible during the DC-1, and are provided as services.

**Table 2 Design Competences available for the MDA**

Competence	Partner	Type of partner	Country
Initial OAD conceptual synthesis	Delft University of Technology	university	The Netherlands
Aerodynamics performance	DLR	research institution	Germany
Stability & Control aerodynamics	AIRINNOVA	small to medium enterprise	Sweden
High Lift Performance	University of Napoli	university	Italy
Propulsion system performance	CIAM	research institution	Russia
Loads and structural sizing	DLR	research institution	Germany
On-board systems design	Politecnico di Torino	university	Italy
Mission performance	DLR	research institution	Germany
Cost Assessment	RWTH Aachen	university	Germany
Flight dynamics assessment	Delft University of Technology	university	The Netherlands
Design Of Experiment	DLR	research institution	Germany
Response Surface Model and Optimization	ONERA	research institution	France
Aircraft DOE Morphing Capabilities	DLR	research institution	Germany
CFD Euler based aerodynamics for airframe	DLR	research institution	Germany
CFD RANS based aerodynamics for nacelle	TsAGI	research institution	Russia
CFD RANS based aerodynamics low speed	CFSE	small to medium enterprise	Switzerland
FEM based structural analysis	Airbus Defence & Space	industry	Germany
FEM based rudder design	Fokker	industry	The Netherlands

A selection of design competences and tools was deployed for the setup of the DC-1 design process. At the end of the DC-1 all the specialists' design tools were CPACS compatible, the specialist design process integrated within the PIDO RCE or Optimus, and accessible via Brics in the AGILE network(s).

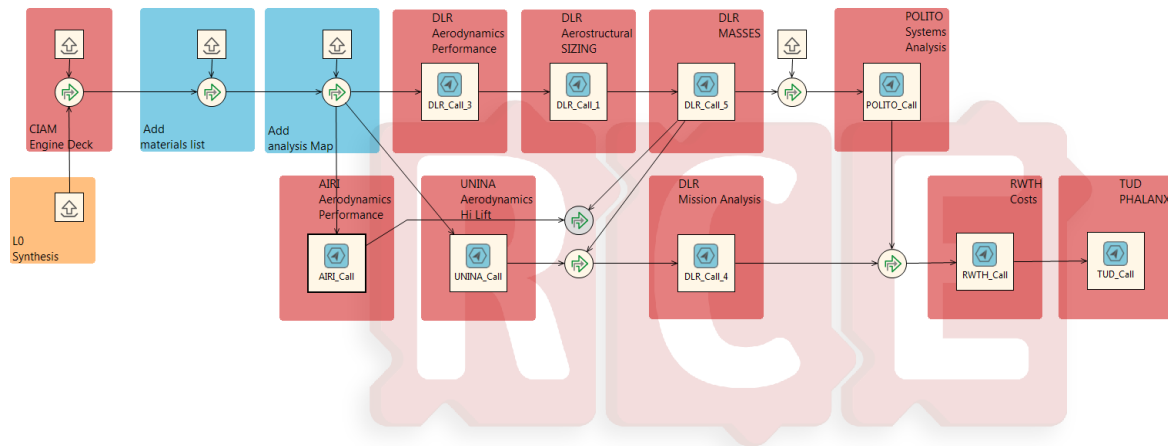
Examples of AGILE Partners’ legacy processes integrated into PIDO environments in the DC-1 are shown in Figure 11. Additional design tools are available in the AGILE pool of tools and competences, and are currently used in the design of multiple use cases in the context of AGILE.



**Figure 11. Examples of DC-1 Design Competence in PIDO. Left: DLR aeroelastic analysis, RCE. Right: POLITO onboard systems design, Optimus. All the design competences are accessible via Brics interfaces supported by the PIDO frameworks.**

**Overall Aircraft Design MDA Process**

As soon as the specialists’ design competences were made CPACS compliant, integrated into the PIDO environments, and made accessible via Brics, the Overall Aircraft Design MDA process was assembled. DLR was responsible as integrator to compose the MDA process by design competences provided as remote services. In DC-1 the MDA was integrated into RCE PIDO and the implementation is shown in Figure 12. During its execution the MDA process was responsible to trigger requests for the remote design competences offered by the specialists as remote services. The MDA process was responsible to orchestrate the sending of input to each of the remote competences, and retrieving the results from each of the competence after the execution. In DC-1 the MDA process (i.e. sequence of services) was “manually” composed, and inspected to guarantee the consistency of the process. The manual process is currently supported by an automated KBE application [18]. Hence, the overall MDA process itself was provided as a service, in order to be - possibly remotely - operated within an optimization process.



**Figure 12. AGILE DC-1 MDA Implementation in RCE PIDO. Each component of the MDA corresponds to a design competence, provided as a remote service via BRICS.**



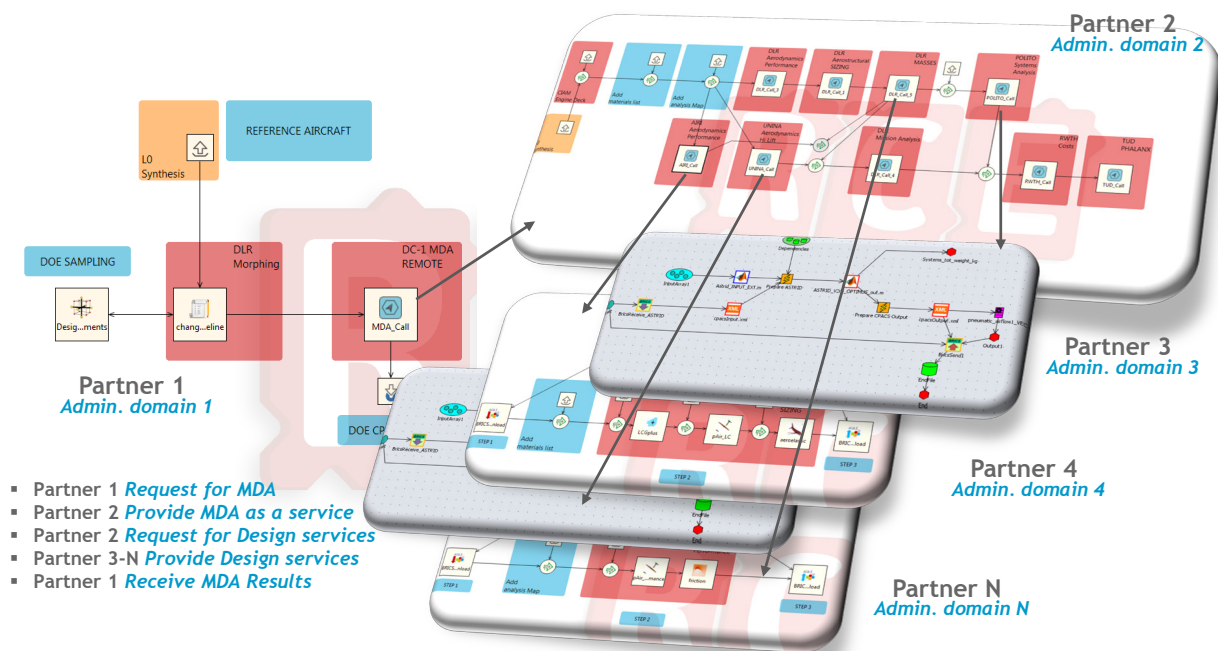
Once the MDA was setup and made available as a remote service by DLR, it was operated by ONERA in order to launch a DOE and Optimization study. The overall approach consisted into the following steps:

1. Generation of a DOE sampling plan and execution of the MDA for each DOE point
2. Generation of a Response Surface Model (RSM) based on the DOE results
3. Optimization task resolved on the RSM
4. Enhancement of the RSM by additional points executed by the MDA
5. Convergence of the results

The DOE component generates the sampling plan to be analyzed, and a Morphing design component is responsible to generate CPACS aircraft models, corresponding to each point of the DOE. Thereafter, each aircraft is analyzed via the collaborative DC-1 MDA process. It is noted that the launched process was the MDA, hosted at DLR; the MDA itself was then responsible for the execution of the specialist services hosted at the multiple partners' sites. . All the results were retrieved from the individual specialist services by the MDA process, and collected from the MDO process, as illustrated in Figure 13. The initial design space explored consisted of 15 DOE initial points, and multiple objective functions were formulated for the solution of the optimization problem. As reference MDO architecture, an MDF formulation [19] has been chosen for the DC-1. The full process is operated in a fully automated mode, accessing the distributed pool of competences within the consortium.

The Collaborative Architecture yielded two main achievements:

1. Interoperability: the architecture is independent from the way in which the competence processes are deployed within each of the connected organizations.
2. Cross-organizational: The whole process is executed in a fully automated cross-company collaborative design workflow.



**Figure 13. AGILE DC-1 Collaborative Architecture. Design Of Experiment connected to the cross-organizational MDA, in a SOA arrangement.**

## VI. Conclusion

In the first year of the AGILE project; the AGILE Paradigm was successfully formalized, implemented, and demonstrated. The AGILE Collaborative Architecture, a main conceptual element of the AGILE Paradigm, is described and presented in the present paper. All the elements of the collaborative architecture implemented in AGILE are described, and demonstrated through the application to the design of a reference aircraft design task. To the authors' knowledge the described use case represents the first successful collaborative aircraft design process which is executed in a fully automated way, thereby integrating competences, tools and processes hosted at multiple organizations. Deployment elements and steps of the Collaborative Architecture are presented in a generalized form, and in an AGILE project specific implementation. The AGILE development framework and its Collaborative Architecture elements presented in this paper, are currently used in multiple AGILE MDO use cases [20].

The AGILE Collaborative Architecture provides the following:

- For AGILE partners and other collaborative MDA/MDO workflow developers and users: The AGILE Collaborative Architecture including a standard data format (CPACS), two PIDO tools (RCE and Optimus) and a non-intrusive integration technology (Brics) enables the partners to define, to implement, to experiment with and to experience real operational collaborative workflows.
- For AGILE partners, other collaborative MDA/MDO workflow developers and users, and other engineers: The AGILE Collaborative Architecture enables collaborating engineers to work across organization borders while complying with the applicable company security policies. The technical details of cross-organizational orchestration and data exchanges are solved isolated from development, deployment and usage of collaborative workflows.
- For AGILE partners and other competence providers: The AGILE Collaborative Architecture enables the AGILE partners to define and to deploy their competences in an "as a service" style.

## Acknowledgments

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**NLR**

Anthony Fokkerweg 2

1059 CM Amsterdam, The Netherlands

p) +31 88 511 3113 f) +31 88 511 3210

e) [info@nlr.nl](mailto:info@nlr.nl) i) [www.nlr.nl](http://www.nlr.nl)