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AGILE Paradigm: The next generation collaborative MDO for the development of aeronautical systems

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ABSTRACT

The research and innovation EU funded AGILE project has developed the next generation of aircraft Multidisciplinary Design and Optimization (MDO) processes, which target significant reductions in aircraft development costs and time to market, leading to more cost-effective and greener aircraft solutions. 19 industry, research and academia partners from Europe, Canada and Russia have developed solutions to cope with the challenges of collaborative design and optimization of complex aeronautical products. In order to accelerate the deployment of large-scale, collaborative multidisciplinary design and optimization, a novel approach, the so-called *"AGILE Paradigm"*, has been conceived. The AGILE Paradigm is defined as a *"blueprint for MDO"*, accelerating the deployment and the operations of collaborative *"MDO systems"* and enabling the development of complex products practiced by multi-site and cross-organizational design teams, having heterogeneous expertise. A set of technologies has been developed by the AGILE consortium to enable the implementation of the AGILE Paradigm principles, thus delivering not only an abstract formalization of the approach, but also an applicable framework. The collection of all the technologies constitutes the so-called *"AGILE Framework"*, which has been applied for the design and the optimization of multiple aircraft configurations. The ambition of the AGILE Paradigm was set to reduce the lead time of 40% with respect to the current state-of-the-art. This work reviews the evolution of the MDO systems, underlines the open challenges tackled by the AGILE project, and introduces the main architectural concepts behind the AGILE Paradigm. Thereafter, an overview of the application design cases is presented, focusing of the main challenges and achievements. The AGILE technologies enabled the consortium to formulate and to solve in 15 months 7 MDO applications in parallel for the development of 7 novel aircraft configurations, demonstrating time savings beyond the 40% goal.

1. Introduction

A major challenge in the transport sector is making growth and sustainability compatible by decoupling environmental impacts from economic growth. At the same time the competitiveness and innovative character of the transport industry needs to be secured. Economic crisis, increasing scarcity of non-renewable energy sources, aging, migration and internal mobility, urbanization, and globalization of the economy are practical challenges to be faced by transport research. These challenges cannot be met by further squeezing out existing technologies alone. Therefore, the aviation industry needs highly innovative solutions, including unconventional concepts, disruptive technologies and other step-changing approaches [1]. This innovation dimension is of outstanding relevance, and requires full exploitation as identified in the "Europe 2020 Flagship Initiative Innovation Union" [2]. The development of disruptive technologies and unconventional solutions cannot be achieved without integration and optimization on system-level, of physics-based simulations with the appropriate level of fidelity. Additionally, the distribution of work and risk along the supply chain is changing fundamentally. The ongoing trend of outsourcing, combined with increasing technical responsibility of lower tier suppliers, clearly shows that the successful suppliers of tomorrow must be able to access, operate with and contribute to system-level analysis and optimization. At the same time, the specific disciplinary expertise need to be accessible by the product integrator, which could make early use of these to perform the analysis in support of the overall architecture evaluation. To a large extent, highly valuable contributions can be expected from

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Nomenclature

AGILE	= Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
CAx	= Computer Aided technologies
CPACS	= Common Parametric Aircraft Configuration Schema
DC	= Design Campaign
DfX	= Design for X
DOE	= Design Of Experiments
I/O	= Input/Output
IPR	= Intellectual Property Rights
IT	= Information Technology
KBE	= Knowledge Based Engineering
MDA	= Multidisciplinary Design Analysis
MDO	= Multidisciplinary Design Optimization
OAD	= Overall Aircraft Design
PDP	= Product Development Process
PIDO	= Process Integration and Design Optimization
RCE	= Remote Component Environment
RSM	= Response Surface Model
SOA	= Service Oriented Architecture
SOTA	= State Of The Art
TLAR	= Top Level Aircraft Requirements
XDSM	= eXtended Design Structure Matrix

high-tech and start-up small and medium sized enterprises (SME) as well as from research (RES) and academia (HES), both from the aeronautical sector and from cross-border research. Nevertheless, by their nature, an individual SME, RES or HES alone cannot establish all the competencies required for the development of a complete system. Current aircraft development programs are established as collaborative and multi-organizational design processes. A major challenge hampering cost-effective design processes is the 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 among different organizations, and across 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. Multidisciplinary Design and Optimization (MDO or MDAO) [3–5] techniques promise to provide key competences in such a paradigm shift. As already acknowledged by Belie [6], although very successful MDO applications have been demonstrated for a subset of disciplines, the ultimate value of MDO will be in its ability to optimize the aircraft as a whole system. The major benefits are expected for the development of novel designs [7], for which inter-dependencies, and design drivers may still need to be unveiled. Furthermore, the extensive ongoing virtualization of the entire life-cycle of products (from design to production) opens new fields of applications for MDO in order to support the decision making, accounting also for manufacturing, operations, and all the stages of the development. The state-of-the-art MDO capabilities can rely on high performance computing infrastructures, efficient optimization algorithms [8] and strategies [9], sophisticated simulation-based analyses in all the flight physics domains [10], and robust process management and integration frameworks [11]. However, due to the technical, management, and socio-technical challenges [12] encountered during the setup and the operations of such complex design systems, the exploitation of the full MDO potentials for the development of a complete aircraft is still an open challenge. As pointed out in a workshop arranged by the National Science Foundation in 2011 [13], during the last decade the MDO community has shifted its focus: although many of the MDO algorithms to search the design space matured into industrial applications, many developments are still necessary to put designers "back in the loop". A workshop hosted by the ICAS (International Council of Aeronautical Sciences) in 2015 on Complex Systems Integration [14] has highlighted the necessity to develop novel methodologies which should encapsulate knowledge and skills in order to be able to manage the increasing design complexities. Such a shift towards "modeling knowledge" is addressed by Zhang [15] as the next step necessary to the evolution of aeronautical complex systems. Nevertheless, the exploitation of the full MDO potentials for the development of a complete aircraft is still an open challenge. Analyzing the current generation of MDO design systems, the authors have identified that major obstacles are largely related to the efforts required to setup and deploy (more than resolve) the complex collaborative development process. Ciampa et al. [16,17] quantified that 60%–80% of the project time may be necessary to setup such a process. Many of the above mentioned challenges are addressed in the AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) [18] EU funded H2020 research & innovation project, coordinated by the German Aerospace Center (DLR). The AGILE project has developed the next generation of aircraft MDO processes enabling significant reductions in aircraft development costs and time to market, leading to more cost-effective and greener aircraft solutions. AGILE has conceived a novel design approach, the so-called "*AGILE Paradigm*", shifting the focus on accelerating the deployment and the operations of collaborative, large-scale design and optimization frameworks. Section 2 provides an overview on the evolution of the MDO systems, and the open challenges. Section 3 introduces the AGILE project's main objectives and activities. In section 4 the AGILE Paradigm is introduced and described in all its conceptual architectural elements. The overarching implementation of the AGILE Framework is presented Section 5. Section 6 provides an overview of the AGILE MDO use cases solved during the project by deploying the AGILE Framework. Section 7 provides the conclusions on the major achievements and main project's deliverables enabling the broader MDO community to access the AGILE Paradigm and its technologies.

2. The evolution of MDO systems

Techniques and methodologies supporting the development of aerospace products have been under development within the MDO research field for more than three decades. During this time, enormous progress has been achieved, and MDO has expanded its domain of application. Nevertheless, the achievements in today's aeronautical projects do not exploit yet the full potentials of MDO. Although significant improvements have been made in the capability to handle complex design problems, industrial applications are lagging behind the performance level which should, theoretically, be at our reach. The underlying question is not one of computational performance, software capabilities or IT frameworks. It is how these powerful tools are used in today's research, development and engineering projects. The most sophisticated integrated design platforms and high-performance computing will not deliver their full potential if they are not efficiently put into action. This section at first addresses the nature of MDO applications, and the evolution of MDO systems, thereafter exposes the challenges still hampering the introduction of MDO in large-scale product developments.

2.1. The saga of MDO promises

In the last 30 years of development, MDO has promised to enhance the performance of aeronautical products in multiple aspects, and has addressed multiple perspectives in which engineers operate. Among the major benefit which are commonly acknowledged, there are:

- Exploiting the synergy between multiple disciplines in order to achieve better performances with respect to conventional design processes.
- Enabling the design of novel aircraft configurations and supporting the de-risking of novel technologies.
- Providing a systematic exploration of the design space and enhancing the understanding of complex products.
- Leveraging the automation to reduce non-creative and repetitive activities.

Fig. 1 provides a schematic representation regarding the fields of MDO applications in aeronautics appeared in the last decades, which are briefly described thereafter.

Multidisciplinary: this is the natural application for MDO in aircraft design. MDO promises to exploit the synergy between multiple disciplines in order to achieve better product's performances, and to identify novel trends. The partitioning strategy of the optimization process, or MDO architecture, selected is often driven by organizational aspects (e.g. disciplinary departments), and the availability of legacy development processes already in place. The number of disciplines involved and the complexity of their connections are constantly increasing, but still not sufficient to formulate a complete MDO problem accounting for all the disciplinary domains required by real scale aircraft development applications.

Operational scenarios: As a result of the extension of the disciplines involved, MDO methodologies are deployed not only for the design of the aircraft product itself, but also for the identification of the best operational scenarios (e.g. considering the operational aspects of an airline fleet). In recent studies the optimization of both the aircraft product and the operational performance are included into a larger optimization problem [19].

Novel technologies: MDO promises to support the exploration of an extended design space, as addressed by novel aircraft configurations and novel technologies. The claim here is that only by making use of MDO it is possible to find a feasible solution, and larger benefits are expected for novel aircraft configurations [7]. A recent example of a large-scale MDO process deployed for a strut-braced wing aircraft is presented in Ref. [20].

Supply chain: Recently, the virtualization efforts of aircraft design products, and of the associated processes (e.g. design and manufacturing), opened new applications for MDO methodologies. When looking at the relation between the number of parts defining an aircraft product, and the number of companies and specialists (from the OEM to the suppliers) involved, MDO methodologies promise to be a key enabler for the integration of all these components into a single development process.

2.2. The generations of MDO systems

MDO design systems developed over the last decades, as well as the modus operandi of such systems, have changed significantly. MDO systems evolved from monolithic design systems, operated by a "single person" on a local infrastructure, to large processing systems, concurrently operated by multiple teams, distributed among several organizations. This evolution trend clearly pairs with the increase of available computational power, as well as the rise in the complexity of the aircraft design tasks and investigations performed during the last decades. The difference MDO generations, previously introduced by the authors in Ref. [16], are briefly addressed in the following.

The well-established "1st generation" MDO refers to applications which tightly integrate disciplinary capabilities and optimizer as a monolithic system, as shown in Fig. 2(a). Such MDO systems are the most computationally efficient from a running time perspective, and are extremely attractive in combination with simulation models whose governing equations merge multiple disciplinary domains. Therefore, research efforts have largely focused on the developments of efficient optimization algorithms, the enhancement of the disciplinary solvers capabilities, as well as efficient parametrization techniques. However,

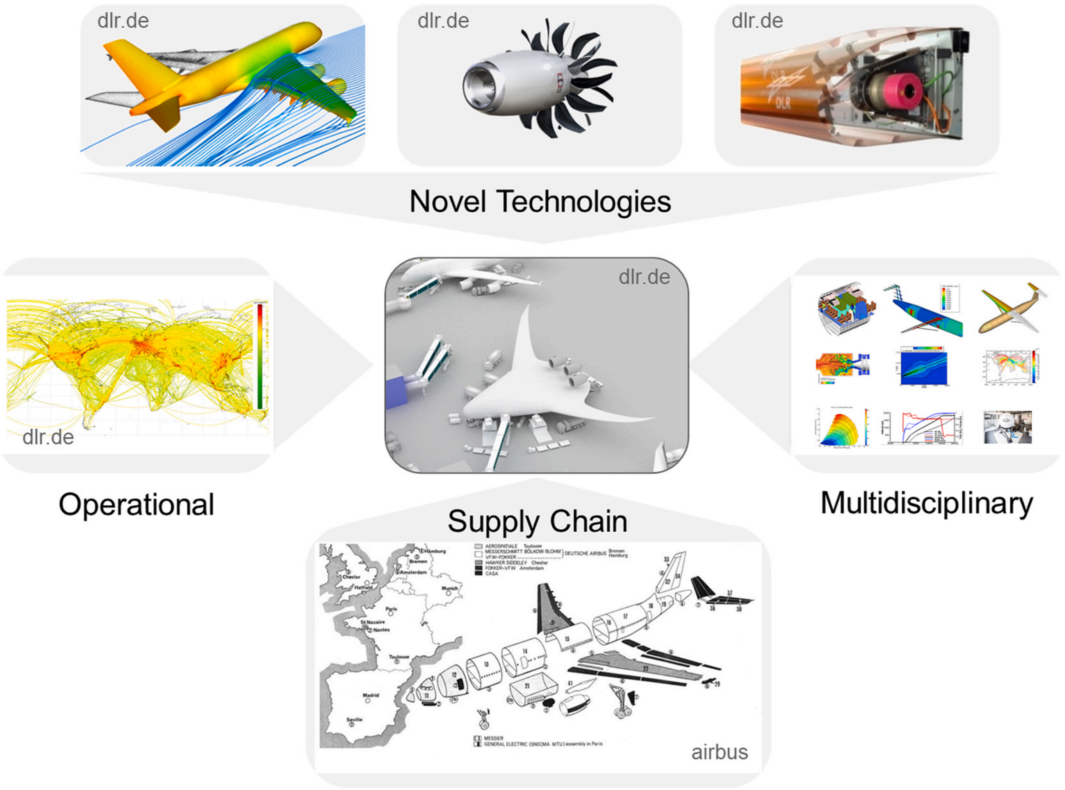
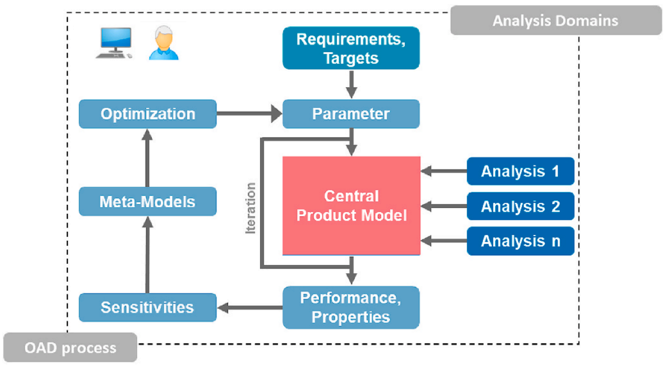
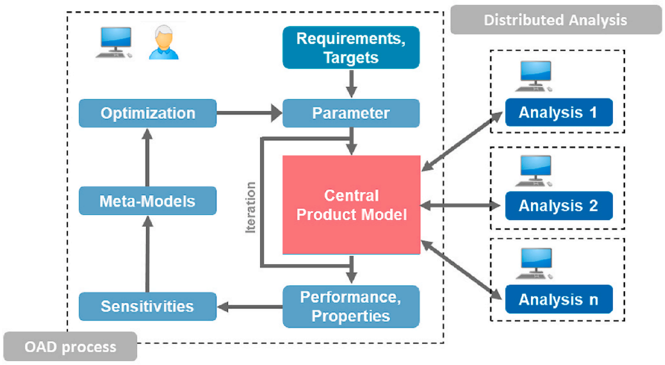


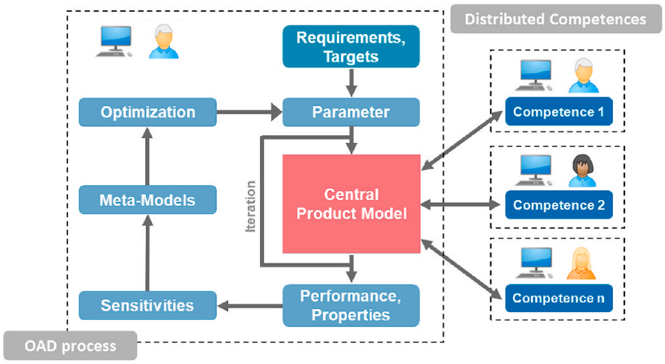
Fig. 1. Nature of MDO aeronautical applications in the last decades.



(a) 1st generation: Integrated MDO Systems



(b) 2nd generation: Distributed MDO Systems



(c) 3rd generation: Collaborative MDO Systems

Fig. 2. Evolution of generations of MDO Systems. The dashed lines indicate different computational domains connected in the MDO system.

the monolithic architecture of such design systems typically lacks the agility to exchange and update the subset of the integrated design modules, when improved disciplinary analysis modules become available or when it is necessary to adapt the system to cope with new configurations. A second limitation is in the scalability of such a design system. As soon as more disciplines and effects are accounted in the design process, the integration into a single system becomes impractical. At present, monolithic design and optimization architectures are efficiently deployed in mainly two scenarios: the first is in conceptual design applications, the second in detailed physics-based optimization with a very limited set of disciplines involved requiring strong couplings (e.g. aero-structural optimization with high-fidelity simulations).

The “2nd generation” is characterized by the distribution of the analysis capabilities on dedicated high performance computational facilities, which are called by a centralized design and optimization process, as shown in Fig. 2(b). In such a setup, dedicated experts are in charge for providing the disciplinary modules, and the team in charge for the design lead assumes the role of process integrator and central optimizer. Multiple design modules need to communicate each other and with the centralized optimization components. Major research efforts have focused on improving the formulation, or architecture, of the design and optimization process decomposition strategy, as well as the functional structure in place within the organizations involved in the design task. The increase in computational power has also lead to an increasing demand for automation in every disciplinary field, with the aim to reduce the manual non-creative activities during the execution of large-scale optimization processes. At present, detailed high-fidelity disciplinary simulations can benefit by the distribution of the computational task over large-scale facilities.

Nowadays, the design of a competitive aircraft product requires the integration of an increasing number of systems (and connected disciplines) in order to find the overall benefit. Furthermore, the complete design is not the endeavor of a single actor anymore, but rather the results of collaboration among hundreds of engineers, distributed among multiple specialized organizations. These limitations are challenged by the “3rd generation” MDO systems, represented in Fig. 2(c). In this case the distribution does not involve only the analysis capabilities, but the distribution of the overall design task. Research has focused of the development of decomposition methods, and approaches, such as concurrent engineering and collaborative optimization, which promise to enable the reality of participative engineering. Due to the complex interactions, one of the priorities of the third generation MDO is to support the human judgment, and lessen the aforementioned complexities. Improvements in visualization techniques, standardization efforts, as well as educational initiatives are undergoing activities with the aim to deliver the expected potentials of MDO. Nevertheless, the implementation of the third generation MDO is not completely realized yet, and its development is at the core of the AGILE project, leading to a system of distributed competences.

More details on the definition of MDO generations and on the timeline of the associated developments are reported in Ref. [16].

2.3. *Collaborative MDO projects*

Multiple projects with focus on MDO have been sponsored by national and international research programs in the previous decades [21].

Most of activities in MDO are advancing specific elements of MDO systems, such as the development of more efficient optimization algorithms or strategies [22], simulation solvers suitable for gradient based optimizations [23,24], and design and optimization integration environments [8,11]. Major international research projects focusing on the development of MDO approaches for large-scale problems, involving multiple disciplines and/or organizations involved, are briefly addressed in the following.

MOB (Multidisciplinary Optimization of a Blended Wing Body): European funded project from 2000 to 2003, with 14 international partners. MOB developed a multidisciplinary optimization process for blended wing body configurations [25]. MOB already contained high-fidelity analysis modules which were interlinked in a distributed network of computers. AGILE continued the MOB work on optimization, with emphasis on the agile deployment of workflows and collaboration techniques for distributed teams. Knowledge-enabled information technologies are further steps beyond the final results of MOB. Considering that MOB required the entire project timeframe of 3 years to establish the optimization of an unconventional configuration, AGILE aimed a large speed-up for the solution of unconventional configurations.

SIMSAC: Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design, European funded project from 2006 to 2009 with 17 international partners [26]. SIMSAC developed a

Computerised Environment for Aircraft Synthesis and Integrated Optimization Methods (CEASIOM) [27]. The focus was placed on methods for simulating and analyzing stability and control of aircraft already in early stages of design with a high level of fidelity. The tools of different disciplines were interconnected on one single computer in a monolithic infrastructure [28]. The objectives of AGILE dedicated to the agility of MDO workflows, optimizations, multi-site computations and collaboration were not addressed by SIMSAC, but the demand for these technologies was identified by the SIMSAC consortium.

VIVACE & CRESCENDO: Virtual product development in the extended virtual enterprise was investigated in the large-scale European funded project CRESCENDO (Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimization) from 2009 to 2012 [29]. CRESCENDO is direct successor to the project VIVACE (Value Improvement Through A Virtual Aeronautical Collaborative Enterprise) 48 months project ended in 2007 [30]. The scope of CRESCENDO is industry-centred collaboration with special emphasis placed on stability over the entire product lifecycle, oriented to the preliminary-detailed design phases. VICACE and CRESCENDO focused on industrial cases, developing standards, such as the developed BDA (Behavioural Digital Aircraft), and distributed working methods addressing IPR security. The objectives of AGILE were touched by CRESCENDO and its precursors. Nevertheless, these focused on the implementation and operation of MDO systems, but not on accelerating the deployment of such processes, which instead is largely addressed by AGILE project.

TOICA (Thermal Overall Integrated Conception of Aircraft): European funded project from 2013 to 2016 with 36 partners [31]. TOICA investigated novel techniques to manage aircraft thermal behavior at the very early stages of development, on two aircraft configurations with EIS 2020 and 2030. Although focus was on thermally optimized aircraft concepts, multiple technologies were developed enabling a flexible and integrated multi-level, multi-disciplinary approaches and architectures trade-offs. Although TOICA delivered secure collaboration methods for cross-organizational simulations, the project did not focus on methodologies to facilitate the deployment of large-scale MDO systems.

2.4. *Challenges in MDO deployment*

Although research focus and applications in MDO projects can largely vary, for every deployed MDO system the following main phases can be identified, as schematically illustrated in Fig. 3:

1. Setup phase
2. Operational phase
3. Solution phase

During the **setup phase**, the main activities include: the formulation of the design task and the definition of the MDO problem to be solved, the pre-selection of the design drivers, the preparation of interfaces and the connection of the distributed design competences (such as disciplinary simulation tools), the deployment of an IT infrastructure enabling the transfer of data among partners and organizations. During this phase the entire design process is formulated first, and implemented into a design and optimization system (either with a monolithic or distributed architecture).

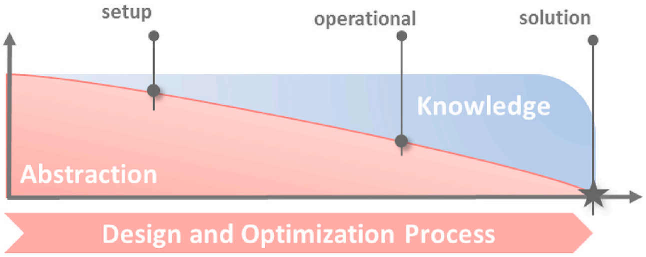


Fig. 3. Phases of MDO based processes.

During the **operational phase**, the assembled design environment is executed to determine the product's properties and to explore a prescribed design space. Human judgment is involved in the assessment of the results, or to determine if the process needs to be re-configured, for instance by including extra analysis or additional details. This phase represents the stage in which most of the data are generated and exchanged among the different parties involved. Large enhancements have been achieved targeting the operational phase, such as the automation of individual disciplinary design capabilities, the formulation of efficient decomposition strategies, and exploitation of parallel computing. Trends illustrate that MDO based design may lead to an increase in the time spent in reasoning on the results, despite the longer time required to assemble the MDO system with respect to legacy approaches.

In the **solution phase** the main challenges are related to achieving convergence of the design and optimization process and to select an optimal solution, and even more important a robust one, via efficient optimization and data analysis techniques. Large efforts in MDO have been dedicated to the development of such optimization capabilities, and nowadays many algorithms are available to the community as out-of-the-shelf solutions.

Although each phase is associated with own specific challenges, the authors have experienced that major obstacles in the current generation of MDO systems are largely related to the efforts required to setup complex collaborative frameworks. Independently on the computational power available, when the integration of a large number of disciplines is planned a relevant part of the project time is spent in the initial setup phase of the MDO process. Activities such as the complete definition and deployment of the design process, the development of interfaces between the heterogeneous components, the identification of input-output relations during the integration require huge efforts. Ciampa et al. quantified that 60%–80% of the project time may be necessary to setup such a process [16] for large-scale aircraft MDO problems. It is noted that all of the previously mentioned MDO projects have focused on the development of elements enhancing the execution of the MDO processes, and therefore accelerating the solution phase. Nevertheless, none has focused on developing methodologies or solutions dedicated to the formulation of the MDO processes, in order to accelerate the setup and the operation of MDO systems. The challenge is even higher when knowledge and background are diversified among the partners providing the disciplinary capabilities. Furthermore, even when such a computational system is established, the resulting implementation is often too stiff to be adapted during the operational phases to different scenarios, e.g. an additional requirements has to be included into the problem, or a new competence has to be added in the design process.

The observed impacts on MDO applications will typically lead to:

- A reduction of the design space under investigation both in depth (less effects accounted per competence) and in breadth (less disciplines or parameters), for the sake of completing the project.
- The realization of a MDO system whose architecture potentialities are not fully exploited or utilized for the problem initially thought, and which cannot easily be re-configured.

The authors advocate that the current *lack of agility* is among the main reasons hampering MDO to step forward and be deployed for real-scale industrial applications, and that the next generation of MDO systems, such as the one developed in AGILE, will need to support the collaborative design team through all the identified three main phases. The mentioned lack of agility stems from multiple technical and non-technical difficulties which are inherent to the large-scale and cross-organizational nature of collaborative development processes, such as required for aeronautical systems. Main challenges faced by the authors in multiple MDO projects include:

Speaking the same language between models of different disciplines and provided by different partners. Within large-scale MDO processes, the vocabulary adopted by the different stakeholders might be very different in syntax and semantic. The challenges include guaranteeing consistency among the multiple disciplinary models and abstractions generated for each of the design competence, and coherency of the level of details of the simulations between the multiple design competences selected. The adoption of standards might ease the exchanging of data, but in multiple domains there is a lack of established standards, and different organization model and store legacy processes and legacy products with ad-hoc representations. The needed of centralized neutral representations might reduce the ambiguity and the assumptions hidden in the models. Furthermore, a neutral representation might serve as meta-description in order to transfer data among organizations, without the necessity to transfer sensitive IPR information.

Integration complexity which translates in identifying the "right sequence" of the computational models to be executed within the design and optimization problem, and in selecting the "right decomposition strategy" (or MDO architectures). For complex products the input and output parameters which are handled and exchanged by models and stakeholders might reach the order of several thousands and the availability of the needed data at every stage of the process need to be guaranteed. Furthermore, during the design exploration, multiple options are investigated, and the design (or optimizatio) process might need to be re-configured multiple times. Adapting the process is always time consuming, and to identify the one which better fits the problem under investigation is a challenge itself. Integration challenges are also related to the choices of fidelity against breadth and resources available.

Managing large design spaces is associated with the large number of parameters to be handled within the design and optimization process. Main challenges include the traceability of the analysis data, the visualization, and the comprehension of multi-dimensional design spaces.

Cross-organizational development needs to account for the access and execution of models which are developed and hosted at computational facilities at the different company branches (or at different companies. The challenge is to establish the governance of the process and enabling the data transfer (automatically), due to IT restrictions or IPR issues.

Collaboration complexity. Here the challenges regard the access and the inspection of analysis results during the MDO execution. User interfaces and accessibility to the MDO frameworks needs to be facilitated, in order to enable the experts to check that the valid regions of the models are respected during the MDO process, or that the optimizer does not exploit a weakness in the formulation. Mindset also needs to be trained to collaborative and concurrent engineering approaches.

3. AGILE project

AGILE [18] has developed Multidisciplinary Design and Optimization technologies, enabling significant reductions in aircraft development costs and time to market, leading to cost-effective and greener aircraft solutions. The project, funded by the EU Horizon 2020 scheme, has started on June 2015 and concluded on November 2018.

3.1. High-level objectives

AGILE's ambition is to advance the state of the art in solving the design and optimization of complex, challenging design problems, such as the development of novel aircraft products, by integration of MDO techniques, collaboration, and knowledge-based technologies. AGILE has set ambitious performance targets to be achieved by the end of the project: a reduction of 20% in time to converge the design of an aircraft and a 40% reduction in time needed to setup and solve a multidisciplinary problem by a team of heterogeneous specialists.

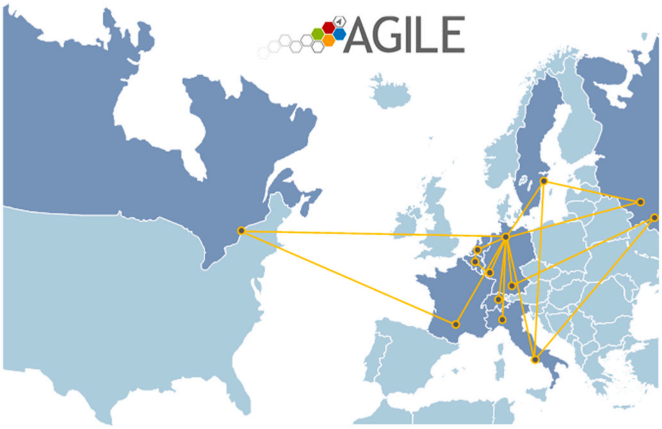
The project objective is translated into the following four technical objectives:

1. The development of advanced MDO methodology and technologies, enabling the effective setup and integration methodologies in the design process reducing the convergence time in aircraft optimization;
2. The development of processes and techniques for efficient multisite collaboration in overall design teams;
3. The development of knowledge-enabled information technologies to support interdisciplinary design task by process formalization and automation;
4. The development and publishing of an open MDO test suite to deploy the AGILE Paradigm.

3.2. The AGILE consortium

The AGILE Consortium is composed of 19 industry, research and academia partners from Europe, Canada and Russia, which have joined their efforts to cope with the challenges of collaborative product development. The composition of the AGILE consortium reflects the heterogeneous structure characteristic of today's aircraft development teams and virtual supply chains: it includes airframe OEMs, suppliers, and specialist design teams. Due to the diversity of partners, multiple collaborative scenarios are formulated and resolved during the project. The geographical distribution of the partners accentuates the collaboration challenges. The overall AGILE Consortium represents a

(a) AGILE partners



(b) AGILE network

Fig. 4. AGILE Consortium: a collaborative MDO network.

collaborative MDO network, as illustrated in Fig. 4(a) and (b).

3.3. AGILE project structure and design campaigns

AGILE is structured in three sequential phases, targeting design cases with increasing levels of complexities, and addressing multiple aircraft configurations and several MDO techniques. The overall work breakdown structure is shown in Fig. 5. In a first phase (Initialization – WP2), a reference aircraft configuration is optimized using state-of-the-art techniques. The reference MDO problem is then used to investigate and benchmark novel optimization techniques individually and later in smart combinations (MDO test bench – WP3). Finally, the most successful approaches are applied to significantly different aircraft configurations (Novel Configurations – WP4). The three sequential phases are embedded within two enabling layers, as show in Fig. 5. The first layer (Collaboration techniques – WP5) targets the development of the technologies enabling distributed collaboration, comprising the process of collaboration between involved specialists, collaborative pre- and post-processing, visualization and the enhancement of existing framework. The second enabling layer (Knowledge enabled technologies – WP6) develops the information technologies, which support the management and the formalization of knowledge within an MDO process.

The parallel activities are clustered in into three sequential phases, named Design Campaigns (DC), with increasing complexity from use case perspective (progressing from conventional aircraft to novel configurations), and MDO environment perspective (from the current state-of-the-art to the AGILE 3rd generation system). During each design campaign, the design system is enhanced by a step forward the full realization of the next generation of MDO processes. For each DC one (or multiple) design and optimization use case(s) is (are) defined. Due to the variety of partners, a complete and extensive set of design competences is available within the consortium, which allows the setup and the resolution of multiple design and optimization cases and collaborative scenarios within each DC. Fig. 6 shows a schematic of the AGILE Design Campaigns, highlighting the advancements of the design system and use cases addressed by each design campaign.

In Phase 1 (DC-1 Month 01 - Month 15) the AGILE team has deployed the reference distributed MDO system and executed the optimization workflow according to current best practice. The reference aircraft is a conventional configuration (Entry Into Service 2020). The MDO system, and the complexity of the design and optimization task have set the metrics of comparison with the AGILE MDO system developed by the end of the project.

In Phase 2 (DC-2 Month 16 – Month 27) different optimization techniques and scenarios have been investigated using the reference MDO framework and the reference aircraft (same conventional aircraft configuration from the previous DC-1). Enhancement methods and technologies developed have been tested against the reference MDO system.

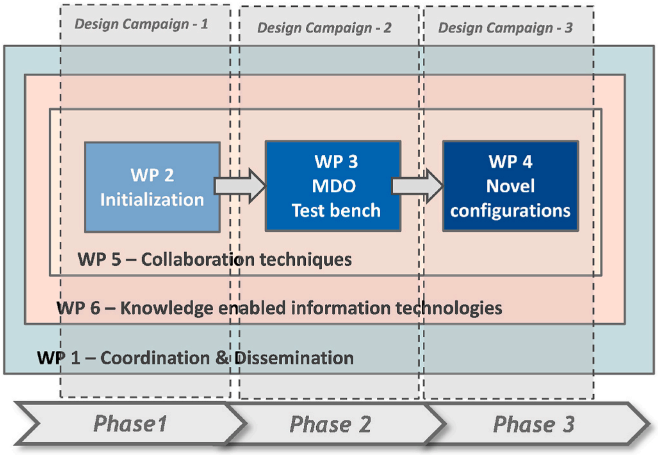


Fig. 5. AGILE Project structure.

In Phase 3 (DC-3 Month 28 – Month 42) the developed AGILE Framework has been applied to multiple novel aircraft configurations in parallel.

Since the measure of the achievable improvement in aircraft performance by MDO techniques is also a function of aircraft concept maturity, the design campaigns setup in AGILE target aircraft concepts with a diversified maturity level and entry into service (EIS) to demonstrate the impact of the developed AGILE technologies on medium-term, and long-term aircraft products, as shown in Fig. 7.

4. AGILE paradigm

In order to enable the third generation of MDO systems the AGILE Consortium has conceived a novel design approach, the so-called “AGILE Paradigm”, supporting the deployment of collaborative, large-scale design and optimization frameworks. The envisioned paradigm shift focuses on the acceleration of the deployment and the operation of cross-organizational MDO systems, which in turns can be effectively exploited to accelerate the development of complex products, such as novel aircraft. In particular, the AGILE Paradigm principles focus on:

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

The technologies developed by the Consortium have been used to implement the AGILE Paradigm, thus making it not only an abstract formalization of a methodology, but an applicable framework: the AGILE Framework. This section addresses the main architectural concepts founding the AGILE Paradigm, whereas technology enablers are addressed in Section 5.

4.1. AGILE paradigm – Overall ambition

The overall AGILE ambition is to reduce the lead-development time by accelerating all the three main phases of the design and optimization processes described in Section 2, as shown in Fig. 8.

The AGILE Paradigm is defined as a “blueprint for MDO” guiding and accelerating the deployment and the operations of collaborative *“MDO systems”* enabling the development of complex products practiced by multi-site and cross-organizational design teams, having heterogeneous expertise. Therefore, as blueprint, the AGILE Paradigm prescribes a series of practices to accelerate and to facilitate the deployment of MDO systems, it indicates how to streamline the operation of MDO systems within the development of complex products, it defines the roles of all the stakeholders engaged in the development, and it indicates how to structure the interfaces and the interactions within the entire supply chain (data, models, and resources involved). Therefore, the main purpose is to enable the effective setup, deployment, and management of an MDO system. An MDO system is here defined as a system delivering a solution to a given design and optimization problem, and which includes:

- Processes for design and optimization (e.g. optimization and partitioning strategies) and product development
- A pool of competences addressing various domains (e.g. disciplinary simulations)
- Stakeholders participating in the development, including their knowledge and expertise

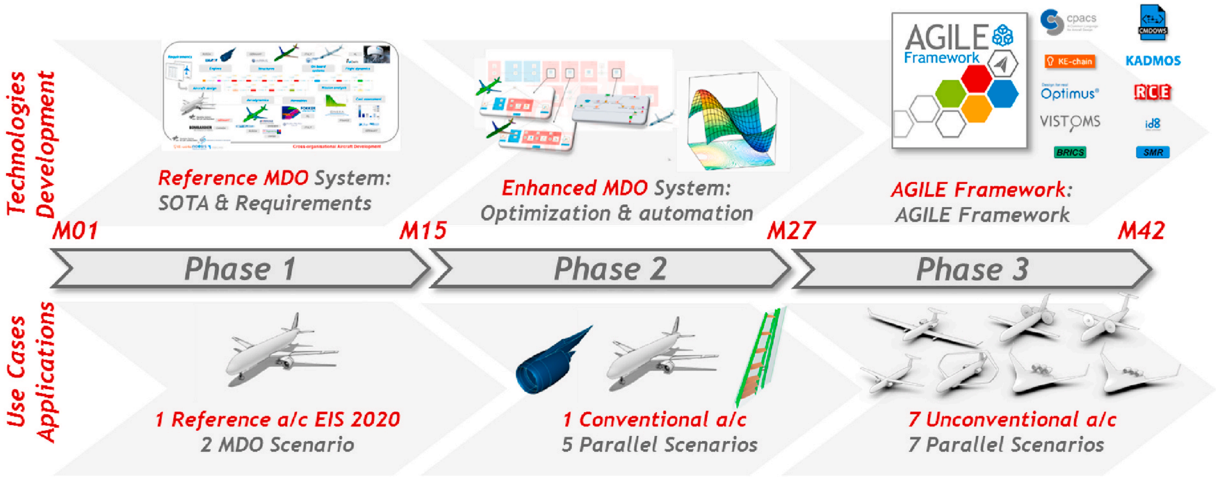


Fig. 6. AGILE design campaigns.

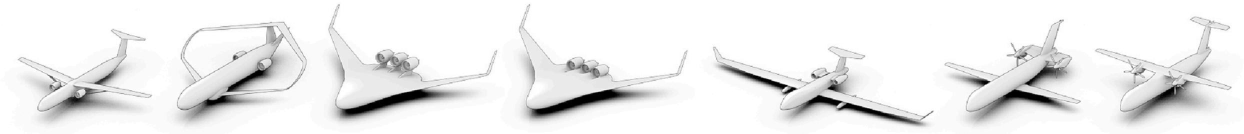


Fig. 7. AGILE Configurations with diversified levels of technology maturity and expected EIS.

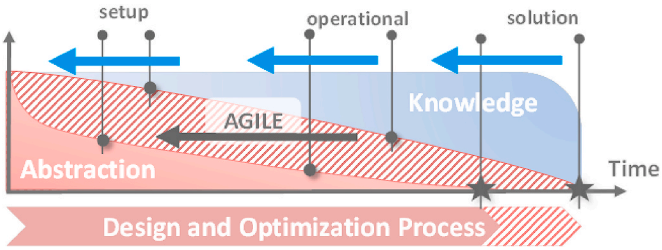


Fig. 8. AGILE paradigm - ambition.

- Models and representations for products and processes which need to be accessed during the design
- Frameworks and platforms supporting the deployment of design and optimization processes, as well as the interactions between models and stakeholders involved

4.2. *AGILE paradigm – Architectural elements*

The overarching AGILE Paradigm architecture, can be described by three major perspectives, illustrated in Fig. 9 and addressed in the following subsections:

1. Process Perspective
2. Organizational Perspective
3. System Structure Perspective

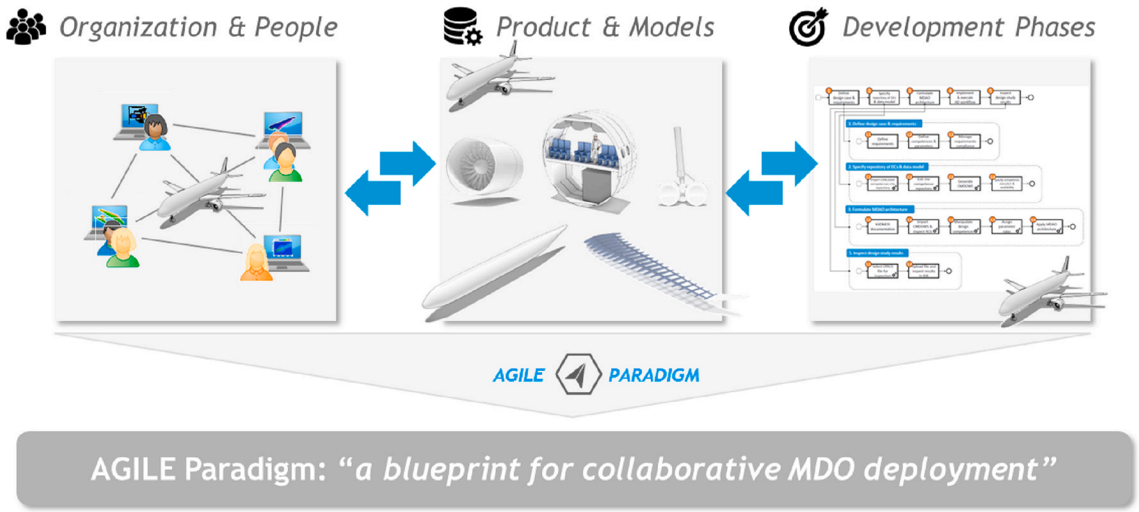


Fig. 9. AGILE paradigm - Architectural perspectives.

The architecture of the AGILE Paradigm is formulated in a generalized way in order to be applicable to the design and optimization of aircraft (or sub-components) as well as to other complex systems. Furthermore, its formulation is suitable to be deployed in the context of different development stages, such as feasibility studies, conceptual design and/or detailed design, and to support multiple *Design for X* (DfX) strategies [32] (e.g. design for performance, design for manufacturing, etc.).

4.2.1. AGILE development process and activities – Process perspective

The AGILE Paradigm addresses the setup and the operation of MDO systems delivering an optimal solution for a given optimization problem. The process perspective describes all the activities and their interactions which are performed during the design and optimization process, with the aim to improve the management of the entire MDO process. A schematic on the major clusters of activities faced during the MDO process is provided in Fig. 10, followed by an overall description for each of the phases.

Define design problem is the phase upstream the development. Main activities include the decision of the requirements and driving parameters of the product, the definition of the design strategy (such as designing for maximum performance or for lower manufacturing costs), and the selection of a certain products' architecture (e.g. a flying wing aircraft). The output of such a phase need to be translated into engineering requirements, and feed forward to the design competences and design processes which needs to be deployed by accounting the decisions made during this phase.

Deploy design competences is an upstream phase as well, and regards the preparation of a pool of competences which is necessary to solve the design and optimization problem. These competences might include disciplinary simulation models (e.g. a noise prediction tools) and optimization capabilities, which are typically developed, maintained, and provided for integration into the design process by different partners, and organizations. Major activities formalized in this phase include the explicit definition of the input and output for each of the design competences, the synchronization of different nomenclature and ontologies behind the heterogeneous models.

Formulate design process is central to the development, and focuses on the formalization of the design and optimization (sub-)process (-es). The main activities include how to structure the design and optimization process and the selection of the MDO strategy, since the same problem can potentially be solved by multiple strategies. The choice might be affected by time constraints (e.g. depending on the computational efforts required by the competences), by the features of the individual competences available (i.e. can provide information such as sensitivities leveraging a certain optimization technique), but also by organizational constraints (i.e. preferring a strategy which facilitate the exchange of data between different departments or maximize the risk sharing). The outcome is the plan of execution of the MDO process.

MDO workflow integration and execution. Most of the technical activities are performed in this phase, which includes the generation of data, the exploration of the design space and the driving of the optimization process. The activities also address the inspections of the disciplinary models, the analysis and verification of the results.

Decision making is the phase downstream the development. Major activity is the selection of the right solution. This phase incudes verification and validation of the solutions (typically available as a tradespaces).

It is necessary to highlight that in such a process changes might occur in every phase, and these are not necessarily unfolding in a sequential order from left to right, but are rather highly iterative. During the exploration of the design space for an initial problem the team might decide that an additional requirement needs to be added, leading to additional competences to be integrated, or to a reconfiguration of the design process and to an update in the implementation of the deployed MDO system. The AGILE process architecture has been formalized to increase the agility to move among the multiple phases, by promoting transparency and traceability of the interactions within and between the multiple phases.

4.2.2. AGILE participative agents – Organizational Perspective

The AGILE Organizational Perspective establishes the effective interactions between the heterogeneous stakeholders which participate in the MDO processes, and formulates multiple roles, the so-called participative agents. The AGILE Paradigm defines for each role a series of actions to be performed during each phase of the developments, streamlining the communication and the decision making within the distributed network. The multiple roles can be well understood by an analogy with instrumental ensembles, such as a symphony orchestra, as shown in Fig. 11 and described in Table 1.

Technical challenges in the collaboration between the multiple agents include to find an agreement on joint setup of models, to schedule execution of simulations, to exchange and compare results. Furthermore, the different agents operate in heterogeneous working

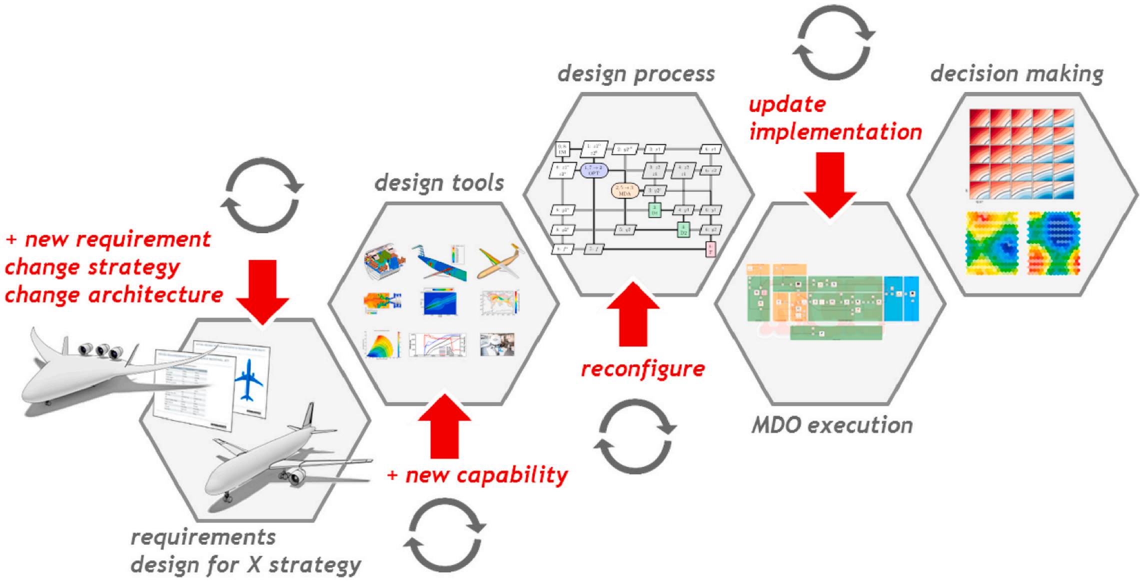


Fig. 10. AGILE process perspective.

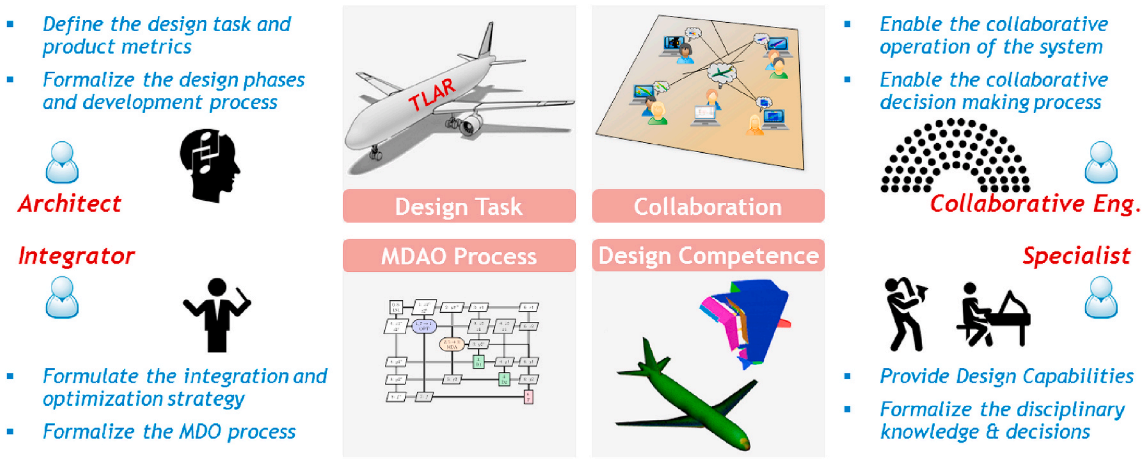


Fig. 11. AGILE organizational perspective.

Table 1
Participative MDO agents in the AGILE Paradigm.

MDO Agents	Responsibility in the MDO task	Orchestra Analogy
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.	Audience
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.	Composer
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.	Conductor
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.	Performers
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.	Ensemble

environments composed of different operating systems, networks, approaches to ways of working, methods, tools, datasets, management and governance procedures. In order to cope with these challenges, AGILE project has formulated the so-called AGILE Collaborative Architecture [33] providing the means to integrate the distributed simulation tools (and the expertise behind the tools) in a so-called service-oriented architecture (SOA). The AGILE SOA, schematically illustrated in Fig. 12, enables the integration of remote services (such as disciplinary simulations provided by the specialists) hosted at different administrative domains (e.g. organizations' networks), within a larger process (such as a MDO process deployed by the integrator) which may be assembled and operated from any of the partners' administrative domains. The described methodology of "gluing" multiple services into a single simulation workflow is scalable up to very complex workflows including a multitude of tools and sub-processes available at different administrative domains. Furthermore, such approach enables also the integration of pre-existing legacy design services from the involved organizations, which was one of the major architectural requirements for the AGILE Framework. On another hand the heterogeneity of the working environment affects the computational efficiency of the execution of the optimization task, due to overheads, transfer of I/O data and files across networks (instead of memory based operations), with respect to a single and integrated solution. However, many of the computational demanding sub-processes (e.g. the aero-structural sizing and optimization services) which integrated into the main design workflow, are implemented into dedicated integrated environments to take advantage of solvers properties (e.g. availability of gradients). Furthermore, such SOA architecture does not only constitute the network backbone for the design process, it also provides solutions for the cross-human and cross-organizational issues occurring in the design process.

4.2.3. AGILE components – MDO system structure perspective

The AGILE Paradigm defines and decomposes the MDO system into a multi-layered structure. The structure of such a perspective is defined as three hierarchical layers: Development Process layer, Automated Design layer, Design Competence layer. A fourth layer, transverse to all other layers is the Data & Schemas layer.

Development Process: Defines all the management and coordination of the activities concerning the end-to-end design phase. The activities are a combination of manual and automated tasks. The business process defined in this layer, supports all the participating AGILE agents through the setup, and the execution phases of the development. Product specifications and requirements, selection of the design competences and optimization strategies are included in this layer.

Automated Design: Defines the design and optimization process which is executed for a specific design analysis or optimization task. This layer orchestrates the MDO process in a specific workflow, depending on the architecture selected, and on the design competence available, and their inter-dependencies. The resulting MDO process is typically implemented into Process Integration and Design Optimization (PIDO) environments.

Design competence: The design competence represent the pool of expertise, analysis and optimization tools, which are available within an organization, or a consortium (as in AGILE), for the design of a product. This layer contains the fundamental bricks to compose the MDO processes in the upper layer.

Data & Schemas: defines the schemas and the data models which are used to describe the design product and processes. They enable the interoperability of both design competences and workflows, and facilitate a faster integration of the multidisciplinary framework.

Table 2 lists the main layers' artifacts (as generalized forms and functions), as well as the corresponding implementation of the modeling

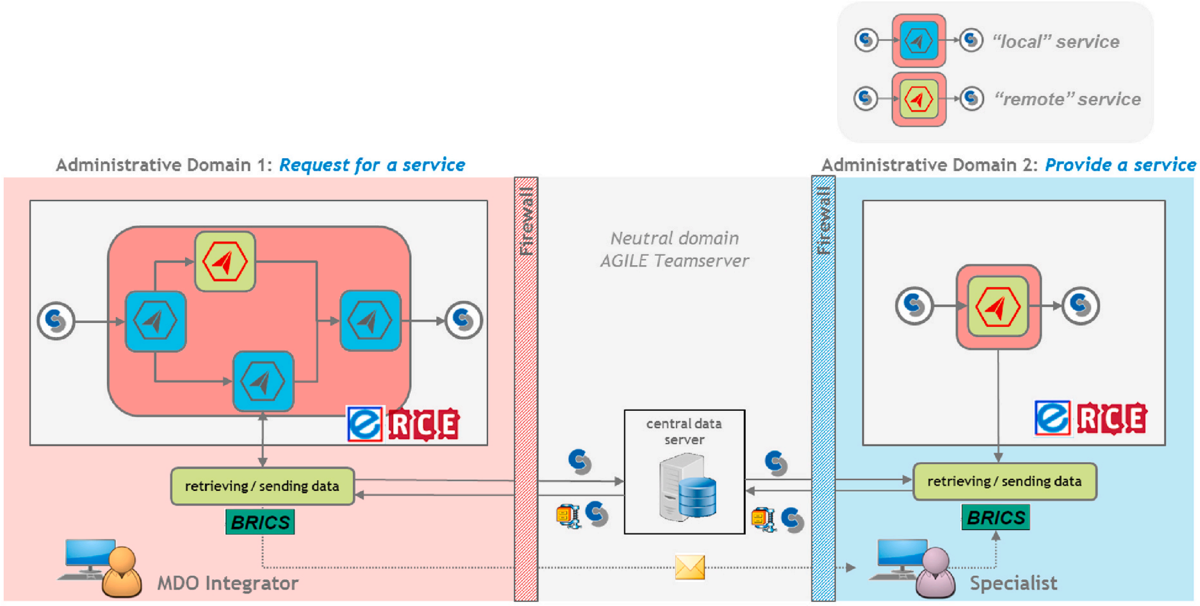


Fig. 12. AGILE Collaborative Architecture – SOA technical solution.

Table 2
Artifacts from the AGILE MDO system and specific implementation details in AGILE project.

AGILE system artifacts			**Implementation in AGILE project**	
Artifact	**Form**	**Function**	**Models**	**Platforms**
Aircraft Design	Product Model	Describe the aircraft and its properties	CPACS, Standards	Design and Optimization Tools
Collaborative MDO Process	Workflow Model	Describe the MDO problem to be solved	CMDOWS, PIDO workflows	RCE, Optimus, Brics
PDP	Process Model	Describe the overall product development	AGILE 5 steps	KE-chain, KADMOS, VISTOMS

and of the IT supporting platforms specifically adopted within the AGILE project. Fig. 13 illustrates the 4 layers described, as well as the artifacts which are delivered by each layer, and the participative agents involved. Details on the interactions between the layers and the platforms detailed are described in the so-called AGILE Knowledge Architecture [34].

5. AGILE framework deployment

The AGILE project has developed a set of technologies enabling the implementation of the AGILE Paradigm approach. The collection of all the technologies constitutes the "AGILE Framework", illustrated in Fig. 14.

All the technology key enablers for the implementation of the AGILE Paradigm's principles have been developed (or made available) by the AGILE Consortium. Therefore, the AGILE Framework makes use of a set of heterogeneous technical solutions, which includes disciplinary tools (i.e. CAx simulations), integration environments (PIDO), optimization

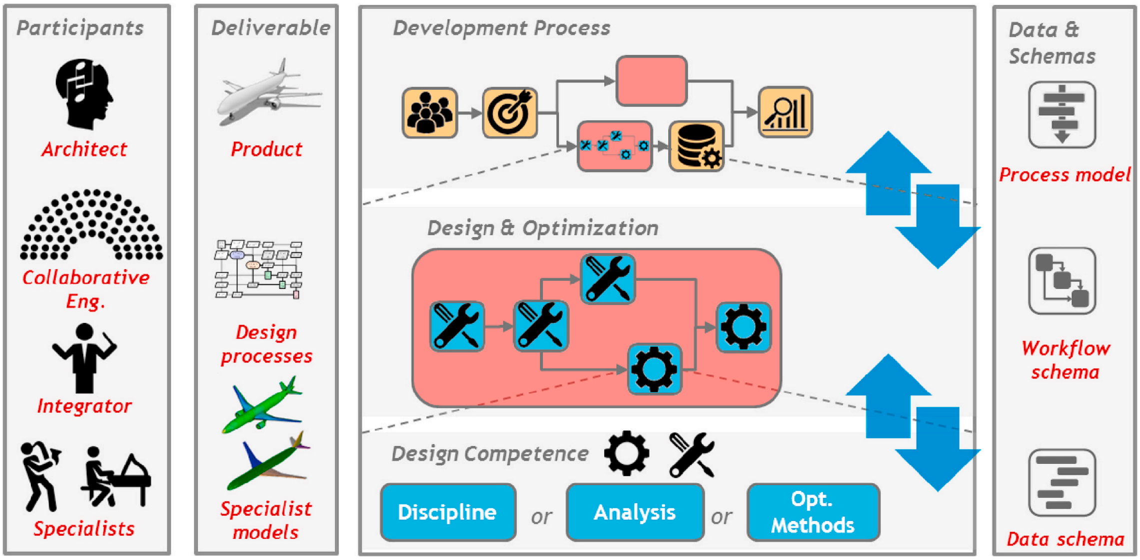


Fig. 13. AGILE MDO system structure perspective.

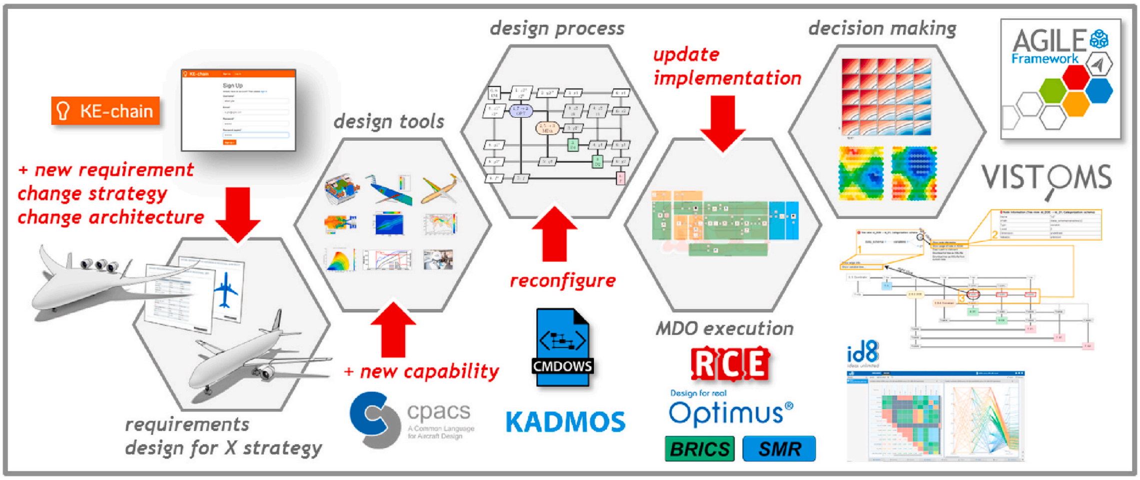


Fig. 14. AGILE framework.

algorithms, KBE systems, web-based process management frameworks, IT solutions enabling the secure data transfer. The main enablers of the AGILE Frameworks are briefly addressed in the following sub-sections.

5.1. *Cross-organizational disciplinary enablers*

In AGILE the aircraft product model is represented by the Common Parametric Aircraft Configuration Scheme (CPACS) [35], developed by DLR. CPACS serves as a central description of the aircraft (and its properties) for all the tools and simulation capabilities available. The application of a common schema for exchanging information drastically reduces the number of interfaces between the multitudes of services to be created. Therefore, CPACS is used to extract the input for the multiple design competences as well as to store 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. The schema is used as common language in aircraft design applications in multiple research and academic institutions [36]. The disciplinary simulation capabilities in AGILE include, among others, aerodynamics and structural solvers, propulsion and on-board systems design tools, flight dynamics simulations capabilities. Fig. 15 shows an example of the AGILE reference aircraft CPACS description, and corresponding disciplinary models generated by the partners' simulation tools.

5.2. *Collaborative MDO process enablers*

In AGILE the MDO processes are integrated as MDO workflows, which describe the design and the optimization to be solved (e.g. variables, constraints), and orchestrate the architecture of the MDO problem. The MDO workflows are configured, deployed and executed by making use of PIDO environments available at the different process integration sites. In AGILE multiple PIDO environments are available. One integration environment used in AGILE is the “Remote Component Environment” (RCE) [37], developed by DLR. NOESIS provides an alternative/complementary collaborative framework by means of Optimus [38]. Both are deployed in AGILE to compose the main processes, as well as disciplinary sub-processes. The cross-organizational mechanism available in AGILE is enabled by Brics [39–41], developed by NLR. Brics provides technology for interconnecting PIDO environments, for which dedicated interfaces have been developed. Therefore, nested complex collaborative MDO workflows, connecting multiple organizations, can be deployed. Thanks to the standardized interface by means of CPACS, sub-processes implemented using different PIDO can be integrated in the same MDO problem. A schematic of workflows in different administrative domains is illustrated in Fig. 16. A neutral formalization of the MDO workflows has been developed in AGILE, and it is provided by the workflow schema, called the Common MDO Workflow Schema (CMDOWS) [42]. Automatic translators from CMDOWS schema to specific PIDO environments have been developed.

5.3. *Product Development Process enablers*

The overall AGILE development process (i.e. aircraft design and optimization in AGILE is described by a five steps approach, which constitutes the top layer of the AGILE Paradigm layered structure. The AGILE development process is illustrated in Fig. 17, showing the major activities performed. The five steps approach is modeled and

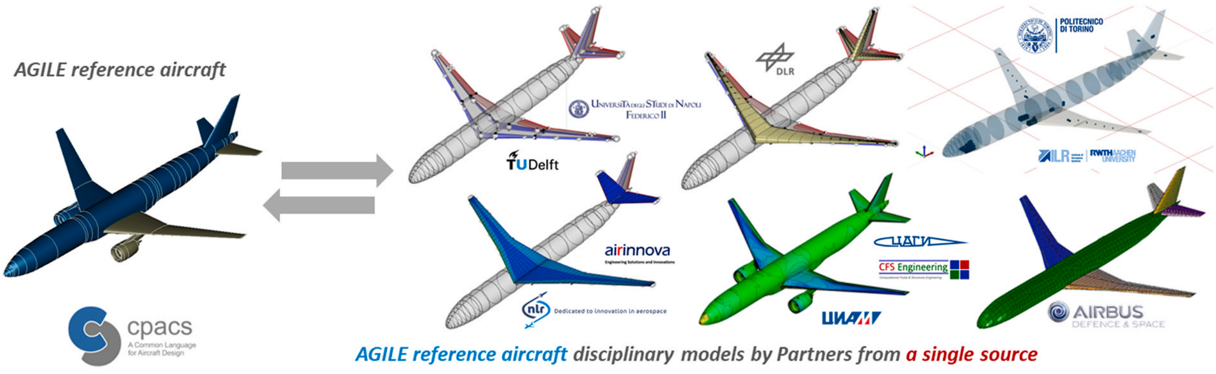


Fig. 15. CPACS representation and disciplinary models generated by the simulation tools available in AGILE project.

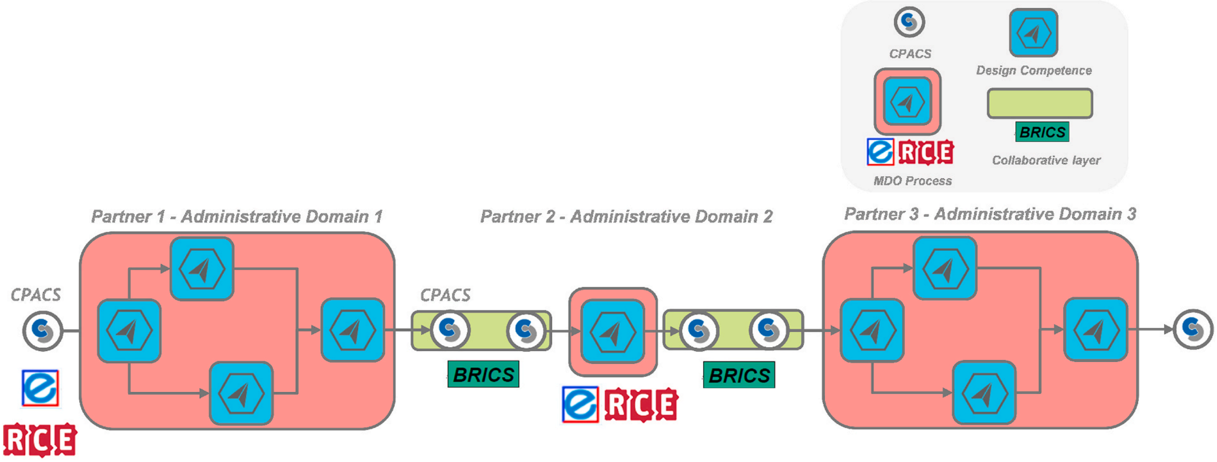


Fig. 16. Connection of PIDO workflows hosted at multiple administrative domains.

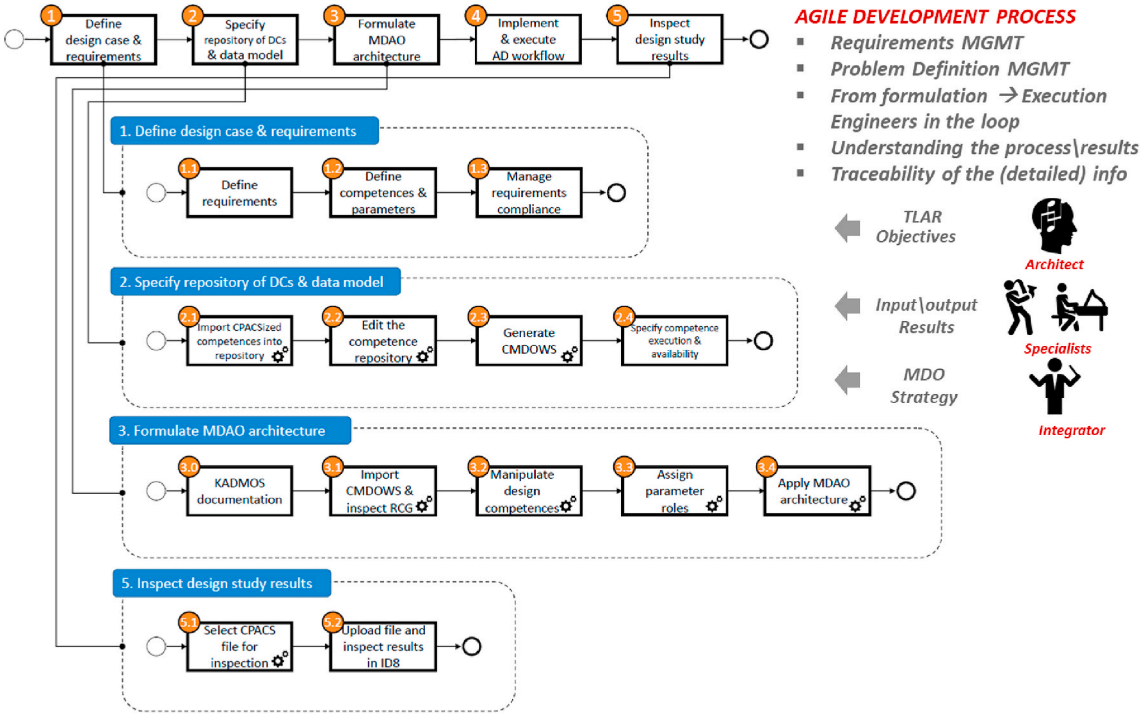


Fig. 17. AGILE Product Development Process (PDP) model.

implemented in the KE-chain web-based platform [43], which is accessible to the entire design teams as a front-end to the AGILE process and technologies. The process supports the management of the requirements, facilitates the selection of the design competences, but also triggers the execution of the workflows process. CPACS and CMDOWS are used within the AGILE development process, details are provided in Ref. [34]. Among the decisions to be operated by the design team, there is the selection of the MDO architecture to be implemented in the workflow. The generation and manipulation of the MDO architecture is provided by KADMOS (Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System) [44], developed within the project. Additionally, the extensive visualization package for MDO processes, VISTOMS [45], has been developed and deployed, supporting all the participative agents' needs at each step of the decision making.

6. AGILE framework applications

The described AGILE Framework has been deployed to solve multiple AGILE collaborative design and optimization use cases, clustered in Design Campaigns (DC) with increasing complexity, as explained in Section 3. Every Design Campaign is comparable in terms of resources and time available. The details on each aircraft configuration, as well as on the corresponding design and optimization tasks, are not intended to be presented in the scope of this overarching paper, but are released in dedicated publications. In the following subsections the main objectives, overall achievements and challenges for each Design Campaign are reported.

Coherently with the lide-cycle of MDO systems already depicted in Fig. 3, each DC is divided into 3 phases:

- **Setup phase**: the design and optimization task(s) is (are) defined and formulated, and the AGILE development framework is deployed.

- **Operational phase**: the design and optimization task(s) is (are) resolved, and the AGILE development framework is operated and reconfigured if needed.
- **Solution phase**: design convergence is achieved and the selected design solution is stored and made available, contributing to build-up the AGILE aircraft database.

6.1. AGILE DC-1: Cross-organizational design of a single conventional aircraft configuration

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 in the design and optimization task of a large regional jet, with Entry Into Service (EIS) 2020. 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. Fig. 18 shows a representation of the DC-1 distributed OAD process. The figure indicates the domains of the specialists' competences which have been integrated into the process, the location where such simulation competences are hosted, and the specific partners providing such a competence with their IT facilities. The pool of design competences available in the consortium comprises design modules for overall aircraft synthesis at the conceptual design stages, and disciplinary simulation capabilities covering multiple levels of complexity and details. The disciplinary simulation capabilities include, among others, aerodynamics and structural solvers, propulsion and on-board systems design tools, flight dynamics simulation models.

Overall objective: the DC-1 served to setup an MDO reference case for the AGILE consortium before the development of the AGILE Paradigm, in order to quantify the time necessary to deploy the MDO process for a given set or requirements. Activities included the definition of the top level aircraft requirements (TLAR) to be satisfied, and the transfer to engineering requirements to the disciplinary experts, and to the OAD process integrator. During the DC-1 it has also been monitored the time necessary for the synchronization of the design competences, the definition of the data to be exchanged and the interfaces between models, the deployment of an MDO process and inspection of the corresponding data flow. All the activities performed during the DC-1 have been analyzed and post-processed in order to deploy the AGILE Paradigm, whose components have been deployed in the successive DC-2 and DC-3.

Overall achievements: an automated design and optimization process, integrating aircraft design capabilities hosted at multiple partners sites and provided as services [33]. Reduction of model inconsistencies is achieved by adopting a common schema (CPACS) for exchanging information between the heterogeneous disciplinary models. It needs to be highlighte that DC-1 has engaged the entire consortium in the solution of one single conventional aircraft configuration and the deployment of one single MDO process.

Overall challenges: the DC-1 has highlighted that time consuming activities were required by the integration of multiple design competences, especially regarding the definition of the design process. An example of faced difficulties was to guarantee that before the execution of a design competence the expected input were available and actually consumed by the competence, and the expected output were provided in a consistent way to be consumed by other competences. The aircraft model description consisted of a few thousands of parameters, hampering the traceability of the data within the distributed process. A large overhead was due to the communications of requirements and design strategies, which has been based on exchanging of ad-hoc documents, diversified in format and nomenclature. Large efforts have also been allocate to prepare the interfaces of the heterogeneous disciplinary models to the CPACS aircraft representation. However, the alternative would have been to generate ad-hoc interfaces among models, has been multiple times proven to be a not flexible approach, and hard to maintain.

6.2. AGILE DC-2: 5 parallel design and optimization studies on a single conventional aircraft

During the Design Campaign 2 (DC-2) multiple MDO formulations and investigation have been performed on the DC-1 aircraft configuration. Although many of the disciplinary design competences were already available and CPACS compliant from the previous DC-1, multiple challenges have been addressed. In particular multiple MDO architectures and novel optimization strategies have been investigated [46,47]. Furthermore, additional design competences, such as high-fidelity simulations [48], have been added in the AGILE pool of competences. As outcome the number of parallel workflows which needed to be setup, formulated, inspected and executed has drastically increased, but retaining the same resources available during DC-1. However, since the aircraft product retained the same requirements, the DC-2 use cases have focused on multiple development scenarios

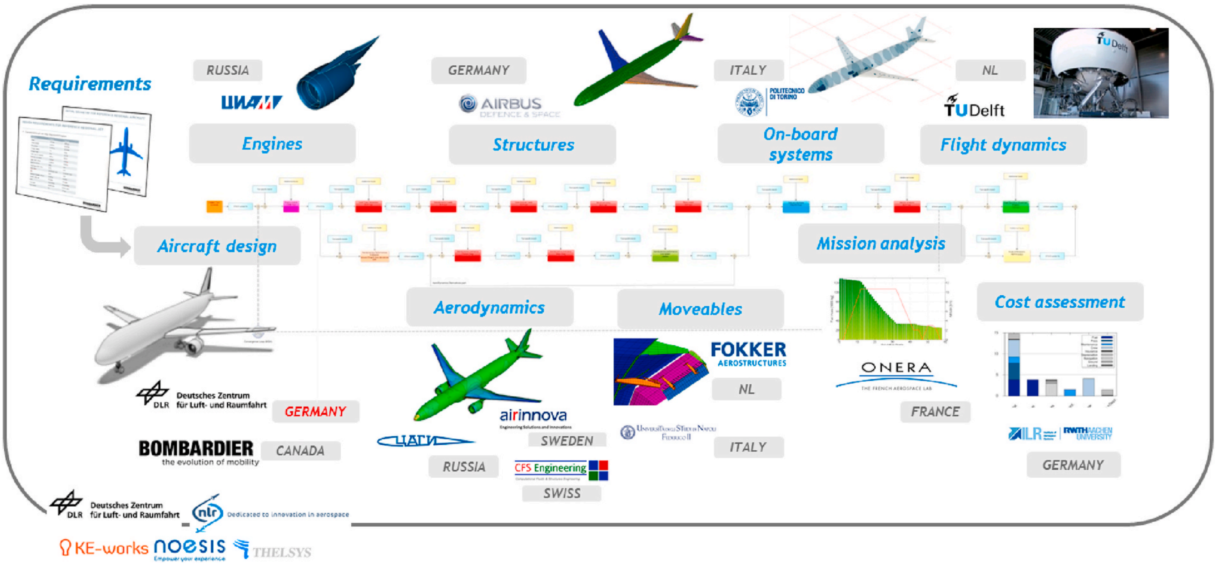


Fig. 18. AGILE DC-1: collaborative design process. Individual competences are distributed multi-site, and hosted at different partner's networks.

within the AGILE supply chain. These included the need for an OEM and a Tier 1 supplier to integrate heterogeneous and closed design processes within a global optimization process [49]. An example is given by the system composed by Airframe manufacturer and the Rudder supplier shown in Fig. 19. Furthermore, a number of challenges have been faced, such as the needs for IPR protection of the exposed data, or the impossibility of Partners to make the own design competences directly accessible as web services. An example is given by the design system composed by the propulsion system OEM, the nacelle design provider, and the on-board systems provider, shown in Fig. 20. All these sub-systems are highly interconnected during the design [50–52], but Partners might have different requirements in terms of accessibility to their own design competences and limitations on sharing of the proprietary data generated.

Overall objective: the DC-2 served to quantify the efforts needed to re-configure an MDO process for different strategies, and to address specific optimization challenges. A total of 5 sub-tasks have been performed in parallel, challenging many of the difficulties faced during the DC-1, such as changing the MDO process, inspecting results if large databases. The DC-2 multiple use cases served to test and assess many of the AGILE Paradigm elements developed during the project.

Overall achievements: During this phase of the project many elements composing the AGILE Paradigm have been developed, enabling early identification of potential inconsistencies in the couplings between the design competences provided before executing the workflows. Collaborative visualization and decision making capabilities of the framework facilitated the discussion and the formalization of the MDO problems within the distributed team. The collaborative capabilities developed within the AGILE framework have enabled the integration of on-line and off-line disciplinary design competences hosted at different partners within an automated MDO process. The optimization strategies implemented have also enabled the coupling of Partners with distinct and independent design systems, in order to achieve a global optimal solution. It is highlighted that although the requirements identification phases was not addresses in DC-2 (since unchanged from DC-1), five parallel MDO processes have been deployed, with the same resources available during the precedent DC-1.

Overall challenges: the DC-2 has highlighted that time consuming activities were required by the managing of information and data by distributed team, and that the accessibility of the agents within the development phases needed to be enhanced.

6.3. AGLE DC-3: 7 parallel design and optimization studies on 7 unconventional aircraft

The Design Campaign 3 (DC-3) challenges the AGILE Paradigm and the implemented AGILE technologies by developing seven novel aircraft configuration in parallel, with the same resources available from the initial design campaigns DC-1. The configurations selected, address multiple physics phenomena (i.e. requiring different set of design competences to be integrated), different EIS (challenging the complexity of the product to be designed), and TLARs (challenging the flexibility of the development process). Fig. 21 shows the models of the design and optimized configurations, and a selection of MDO processes as XDSM representations. It is observed that each configuration has an own MDO process, due to the different nature of the designs, or different drivers of the optimization processes, and different competences integrated into the process.

Additional design competences are added in the AGILE design competence pool, in order to challenge the flexibility of the integration process as well. Partners are involved in multiple configurations, but not necessarily providing the same design services for all of them. Furthermore, each configuration has been selected in order to address different designing challenges. The management for each configuration is assigned to a multiple Architects and Integrators. Therefore, the DC-3 resulted in the need to setup seven complete aircraft development projects, including the assembly of the design team, and the definition and management of the requirements and driving parameters during the development. The following novel aircraft configurations have been addressed during DC-3: Blended Wing Body in two variants (with and without BLI) [53,54], Box Wing, Strut-Braced Wing [55,56], advanced Turboprop in two variants (wing-mounted and rear-mounted engine) [57–59], and a MALE UAV [60,61]. Fig. 22 (a), (b), and (c) and Fig. 23 (a), (b), and (c) show a selection of the design competences integrated within the MDO process for the Strut-Braced Wing and the UAV. It can be noticed that the configurations architecture and requirements are largely different between the use cases.

Overall objective: The DC-3 provides a measure of the agility achieved by AGILE Paradigm, quantifying the impact and the improvements which are enabled by the AGILE technologies with respect to the previous design campaigns. The objective is to challenge the flexibility of the AGILE framework by setting-up and resolving 7 MDO use cases in parallel.

Overall achievements: the AGILE Paradigm, and its architecture described in the previous sections have been implemented in all its elements and applied to multiple use cases. With respect to the DC-2, the deployment of the MDO system is fully formalized in all its phases, including the definition and management of the requirements, the definition of the MDO strategies. The resulting AGILE MDO system provides a framework which is fully operational and provides a cockpit to integrators and architects to successfully deploy and manage complex MDO workflows from a problem definition to an executable workflow. The accessibility to the product and simulation models is enabled via a centralized approach. Inspection of the process and traceability of the data flow are centralized and facilitated by an extensive visualization platform. Furthermore, the design space explored for each of the configurations is much larger with respect to the DC-1, as well as the number of analysis integrated within the process, and the level of fidelity is higher. It is necessary to highlight that in DC-3 seven independent MDO processes needed to be fully setup and deployed. The deployment of the multiple MDO processes in DC-3 has been achieved within less time than needed in DC-1 for a single aircraft, and with comparable resources, which also accelerated the delivery of the solution to the aircraft design problem.

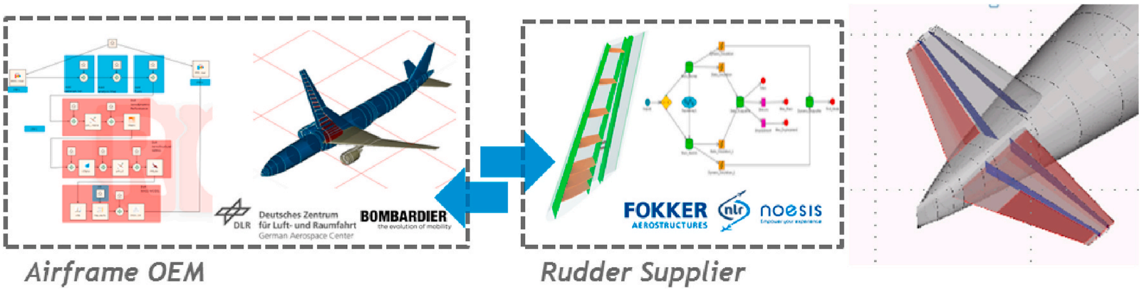


Fig. 19. DC-2 Use case: System composed by Airframe OEM and Rudder Tier 1 supplier.

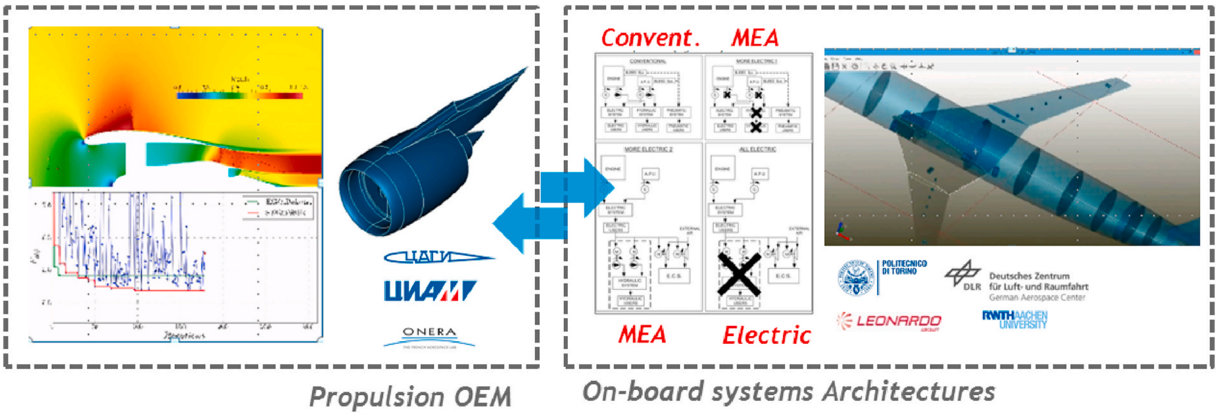


Fig. 20. DC-2 Use Case: System composed by propulsion system OEM, the nacelle design provider, and the on-board systems provider.

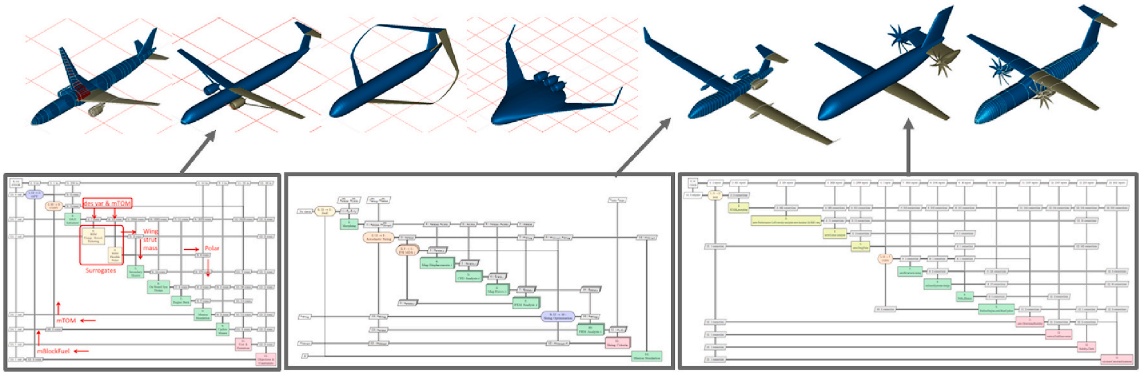
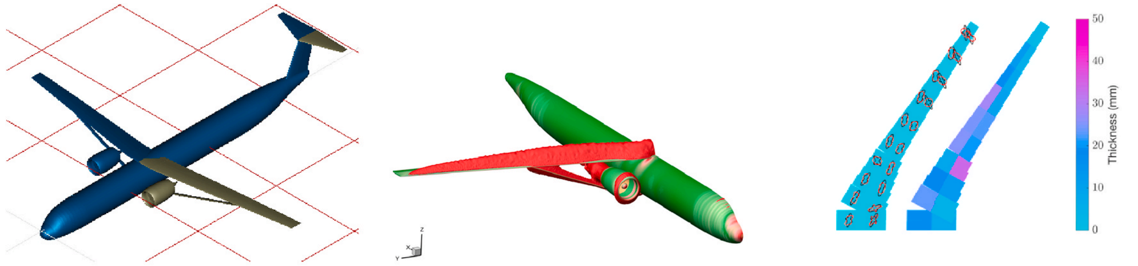


Fig. 21. CPACS files of AGILE configurations developed in parallel in the phase 3 of the project.



(a) CPACS model (DLR) [55] (b) Aerodynamics model (TsAGI) (c) Composite tailored wing model (TU Delft) [56]

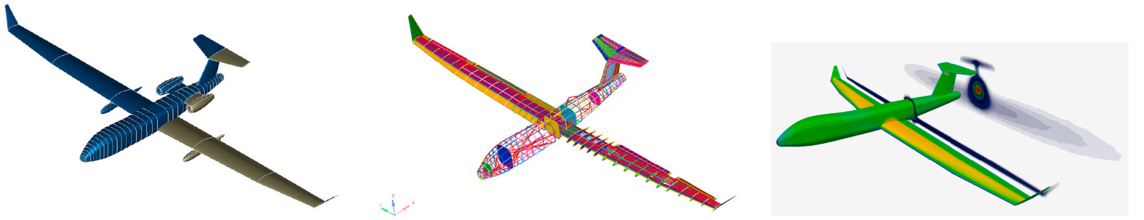
Fig. 22. DC-3 Use case: Strut Braced Wing (SBW) aircraft. Architect and TLAR: Bombardier. MDO Integrator: DLR. Selection of design competences integrated.

Overall challenges: the DC-3 has highlighted many technical challenges which are dealing with large- scale and concurrent application of the technologies developed for the implementation of the AGILE Paradigm. In fact in DC-3 a much larger number of data has been processes, more design competences integrated, and more participants were able to join the design task (with a reduced effort per participant).

7. Results & conclusions

7.1. AGILE overall progresses

Main objectives of AGILE project are to achieve a reduction of 20% in time to converge the design of an aircraft and a 40% in time needed to setup and solve the multidisciplinary problem in a team of heterogeneous specialists. The multiple designs campaigns demonstrated the impact of the AGILE Paradigm principles and the AGILE Framework to meet the main objectives. The long setup time of MDO processes (including the formulation and integration phase), compared to the legacy design approaches, is acknowledged to be one of the main issues discouraging industry from a full adoption of MDO technologies. In the last design campaign (Phase 3) AGILE demonstrated the capability to address 7 challenging aircraft design cases in the sole period of 15 months, during which an uncountable number of workflows has been (re-)formulated, (re-)integrated and (re-)executed in 2 different PIDO environments. 15 months was the same time frame required by the first AGILE design campaign (Phase 1) to address a single aircraft configuration (conventional) when the AGILE Framework and the composing technologies were not available yet. Furthermore, for each of the 7



(a) CPACS model (DLR)

(b) Airframe structural model (AIRBUS D&S) [60]

(c) Aerodynamics model (CFS Engineering)

Fig. 23. DC-3 Use case: UAV MALE aircraft. Architect and TLAR: AIRBUS D&S, LEONARDO. MDO Integrator: DLR. Selection of design competences provided by the consortium.

aircraft, more details and disciplines were integrated in the MDO process, as well as more experts participated into the design and optimization tasks (with respect to the conventional aircraft). An overall assessment of the overall achievements is shown Fig. 24. It can be observed that for each phase a reduced amount of time was needed to setup a set of consistent requirements, as well as to deploy the simulation MDO processes. As a consequence more time was spent on the exploration (and optimization) of the design space for each of the aircraft configurations (i.e. including more disciplines, more effects, more parameters to explore). Detailed comparison of the design space for selected AGILE MDO problems are available in Ref. [62], and the overall achievements by the end of the project are presented in Ref. [63].

Therefore, the drastic time reduction achieved to setup and resolve the MDO problems is beyond the AGILE objectives. The setup reduction time is estimated to be about 40% target, resulting from the time savings in the formulation and integration phases.

Time reduction in formulation. The AGILE technologies responsible to reduce the formulation time are the aforementioned KE-chain, VISTOMS, BRICS, and in particular KADMOS. Through its graph-manipulation approach KADMOS is able to completely automate the 3 stages of the formulation process: 1) generation of the design competence repository, 2) formulation of the fundamental optimization problem, 3) integration of the former into one of the many MDO strategies at hand (i.e. simple design convergence, DOE, various monolithic or distributed MDO architectures). The agility to quickly iterate from one phase to the other of the formulation process is also due to the possibility to store the intermediate results via CMDOWS format, developed during AGILE.

Time reduction in executable workflow integration. As a result of the neutral MDO representation CMDOWS format, and the dedicated CMDOWS parsers developed for RCE and Optimus, the translation of any MDO formulation produced by KADMOS can be immediately translated into executable workflow. Theses workflows can include components that are actually other remote sub-workflows, possibly assembled with a different PIDO tool than the master workflow. BRICS is the technology allowing the master-slave workflows integration in the AGILE SOA approach.

The time-to-convergence reduction challenge. Significant optimization time savings were also achieved by the exploitation of 1) approximation techniques (surrogate models) and 2) advanced optimization algorithms. Concerning the generation of the surrogate models, both existing methods and toolboxes were used, such as the Optimus one or the MultiFit, and new/improved methods developed within AGILE, such as the co-kriging (multi-fidelity) approach and MOE (Mixture of Expert) able to combine more local surrogate models [64]. The use of surrogate models was key to the exploitation of hi-fi analysis in the various design cases [65]. Concerning the optimization, both existing algorithms were used, as those provided by Optimus and DAKOTA, and the newly developed ones, such as the multi-objective NGA (40% faster than other GA based MOO methods) [66] and the SEGOMOE (factor 8 reduction in number of iterations). Details on the optimization problems are available and further references in Ref. [63].

7.2. AGILE main deliverables

The AGILE project has delivered **2 main final open access outcomes**, accessible on the AGILE portal.

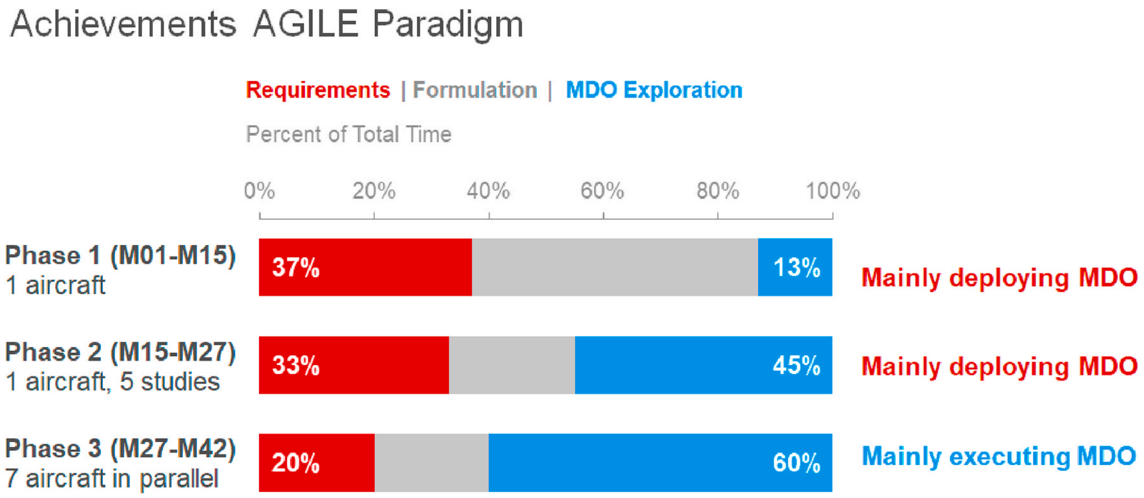


Fig. 24. Overall AGILE Progresses. From 1 conventional aircraft MDO problem solved in 15 months, to 7 unconventional aircraft MDO problems resolved in parallel.

1) **The AGILE novel aircraft configurations database.** This database is the use-cases collection and contains extensive results and digital models of the 7 novel aircraft configurations, designed and optimized for reduced environmental impacts. The database provides a solid foundation to further research related to novel aircraft. The database is available on the AGILE portal, where registered users can download a use-case package. For each aircraft configuration, the package include the aircraft configurations digital models (e.g. CAD, CPACS, FlightGear simulator models as shown in Fig. 25), the design and optimization processes implemented (e.g. XDSM), the design exploration and optimization studies' results, and other discipline specific outcomes. The database is accessible from the AGILE portal [18].

2) **The AGILE Open MDO suite.** The suite contains the AGILE design and optimization technologies, providing accessibility to a very large-scale number of organizations and applications, even beyond the aeronautical applications. The suite is made accessible to external in multiple ways: 1) via a web-based application hosted on the AGILE portal (users can use it as they would navigate on a web page); 2) via a virtual machine containing all the needed components and ready to be used, which enables customization from the users perspective; 3) via a series of repositories hosting the individual technologies (for ad-hoc setup of AGILE technologies within other environments). Extensive tutorials, examples and videos have been prepared. Exploration and optimization studies' results, and other

Fig. 25. AGILE Novel configurations (left) available in the database and corresponding CPACS models (middle) and FlightGear models (right).

discipline specific outcomes. The AGILE Open MDO Suite is accessible from the AGILE portal [18].

7.3. AGILE ACADEMY initiative

The **AGILE ACADEMY** initiative [67,68] was conceived to infuse into academic organizations and educational environments the AGILE Paradigm principles, and to make available the methods and technologies developed within the AGILE project. The AGILE ACADEMY consisted a series of activities which have been launched during the project and carried out in collaboration with the academic and research institutions, supported by the industry partners. The organized activities included supporting students' projects, organizing workshops and courses at universities, organizing open webinars in order to promote and to make available the AGILE technologies to a broader MDO community. The AGILE Open MDO Test Suite provided the enabling technologies. In a first phase, the initiative has been dedicated to the Academic organizations within the AGILE consortium. In a second phase, the activity has been extended to the participation of organizations external to the AGILE consortium. The activities reached out more than 15 organizations external to the project consortium, and world-wide distributed, contributing to forming the next generation of professionals in aviation.

7.4. Conclusions & outlook

The EU funded AGILE project has developed the next generation of aircraft Multidisciplinary Design and Optimization (MDO) processes, enabling significant reductions in aircraft development costs and time to market, leading to more cost-effective and greener aircraft solutions. This paper has introduced the AGILE Paradigm, a novel design approach accelerating the deployment and the operation of collaborative, large-scale design and optimization frameworks. The paper has presented the architectural elements and the main principles founding the AGILE Paradigm, as well as an overview on the developed technology enablers. The AGILE Paradigm approach has been implemented and proven to reduce the time and associated costs for designing conventional and novel aircraft configurations that are expected to enter service between 2035 and 2050. The AGILE Consortium has successfully demonstrated the application of the AGILE methodology and technologies by achieving in 15 months the formulation and the solution of in parallel for the development and the MDO application of 7 novel aircraft configurations. Prior the development of the AGILE technologies, the consortium was able to deploy and resolve the MDO application for the development of 1 conventional aircraft, within the same time frame of 15 months and comparable resources. During the AGILE project a number enhancements have been identified, among others the formalization of the perspectives founding the AGILE Paradigm, as well as of the entire novel approach, by leveraging digital design engineering approaches, such as Model Based Systems Engineering. Other envisioned extensions include the application of the AGILE Paradigm principle to other phases of the development life-cycle (e.g. production, certification, maintenance). Many of these outlook activities are already ongoing [69] and are at the core of the follow-on EU funded research project AGILE4.0 [70] launched in September 2019.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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