DELIVERABLE D 3.2

LESSONS LEARNED. BEST PRACTICES MDO COLLABORATIVE FRAMEWORK

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WorkPackage N°: WP3
Due date of deliverable: 31.04.2022
Actual submission date: 31.01.2023
Document ID: AGILE4.0_D3.2.docx

Grant Agreement number: 815122
Project acronym: AGILE 4.0
Project title: Towards cyber-physical collaborative aircraft development
Start date of the project: 01/09/2019
Duration: 42 months

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THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME UNDER GRANT AGREEMENT NO 815122

DOCUMENT INFORMATION

Document ID	AGILE4.0_Template_Deliverable3.2_v0.5.docx		
Version	0.5		
Version Date	31/01/2022		
Author	T. Lefebvre		
Dissemination level	Public		

APPROVALS

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DOCUMENTS HISTORY

Version	Date	Modification	Authors
0.1	03/12/2022	Creation	T. Lefebvre
0.2	05/01/2023	Updated version	T. Lefebvre
0.3	30/01/2023	First complete version	T. Lefebvre
0.4	31/01/2023	Correct sentences, add some references	T. Lefebvre
0.5	21/04/2023	Check references, typos	T. Lefebvre

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GLOSSARY

Acronym	Signification
AC	Application Case
CPACS	Common Parametric Aircraft Configuration Schema
DOE	Design of Experiment
EGMDO	Efficient Global Multidisciplinary Design Optimization
KADMOS	Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System
LIE	Lightening Indirect Effect
MBSE	Model-Based Systems Engineering
MDA	Multidisciplinary Design Analysis
MDAX	MDAO Workflow Design Accelerator
MDF	Multidisciplinary Design Feasible
MDO	Multidisciplinary Design Optimization
OCE	Operational Collaborative Environment
RCE	Remote Component Environment
RSM	Surrogate Model
RVF	Requirement Verification Framework
PIDO	Process Integration and Design Optimization
SOTA	State Of The Art
SMG	Surrogate Model Generator, broker functionality of the SMR
SMR	Surrogate Model repository
SMT	Surrogate Modeling Toolbox
VISTOMS	VISualiziaton TOol for MDO Systems
WP	Workpackage
XDSM	Extended Design Structure Matrix

1 EXECUTIVE SUMMARY

1.1 Introduction

In the frame of AGILE 4.0 project, WP3 is responsible for the optimization and validation phase. The activities to be conducted can be grouped under three different objectives:

- Support to all Application Cases to set up and operate MDO process
- Provide a final feedback on the Operational Collaborative Environment (OCE) implementation
- Assess the developments of AGILE4.0 project.

This deliverable describes a portion of the activities under the first objective, specifically the support activities for each Application Case (AC). This document provides the lessons learnt and the best practices derived during the Application cases (ACs) design campaigns. The activities carried out during these design campaigns were continuously monitored, and were systematically processed in order to extract the lessons learned and to provide best practice advices.

1.2 Brief description of the work performed and results achieved

In this deliverable D3.2, we report on the main lessons learnt from the optimization set up and execution process across all Application Cases (ACs) of the AGILE 4.0 project. The report begins by providing an overview of the AGILE 4.0 steps, with a particular focus on the Design and Optimization step. The context of each AC is also introduced. Next, we conduct a systematic analysis of the lessons learnt and map them to the Design and Optimization step breakdown. Finally, we derive some best practices for setting up and executing challenging collaborative Multidisciplinary Design Optimization (MDO) workflows

1.3 Deviation from the original objectives

1.3.1 Description of the deviation

This deliverable has experienced an 8 months delay.

1.3.2 Corrective actions

The main corrective actions aim at mitigating the impact of the delay on the other activities of the WP3 and on the Application Cases themselves. To address these aspects, the actions taken have been to increase interactions with the ACs integrators and owners through the establishment of bi-weekly teleconferences to monitor the evolution of the roadmaps, share best practices, identify bottlenecks, and provide quick support. In addition, on-demand meetings have also been organized with each AC.

2 WORK PERFORMED

2.1 Context in AGILE 4.0 project

AGILE 4.0 project is structured into three main layers (Fig. 1), and briefly recalled here:

1. *Application cases layer*: AGILE 4.0 addresses 7 parallel use cases of aircraft collaborative development and optimization scenarios, each one dedicated to a specific aspect in the life cycle of an aeronautical system, i.e., design manufacturing, assembly, certification and maintenance. These use cases are representative of 3 main product development streams: production driven, certification driven and upgrade driven, as detailed in the next section.
2. *Integration and Validation Phases layer*: the development of the digital transformation solution for the supply chain and the implementation strategies for all the use cases, are coordinated in this layer. Structured as series of sequential phases, this layer is responsible to pull the requirements and needs from all the 7 use cases, and push them into the development of the enabling technologies layer. Once the enabling technologies become available in the upper layer, they are pulled in this layer for their integration and applications to the various use cases. The use cases will provide a validation of the enabling technologies and possibly call for their adjustment and extension.
3. *Development enabling technologies layer*: this is the production lab where the necessary (enabling) technical solutions to tackle the various use cases are developed. These include product and process, models, IT platforms, optimization and decision-making techniques and various design tools to address some of the use cases specific needs.

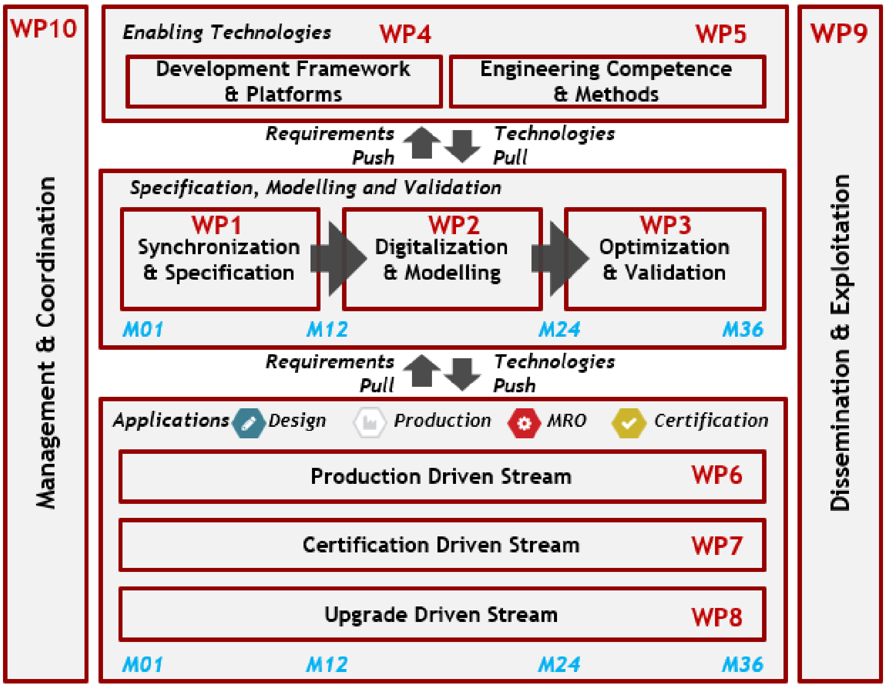


Fig. 1: Overview of AGILE project

WP3 is the last WP of the "Integration and Validation Phases layer" and is in charge of the optimization and validation phase. The activities to be conducted can be gathered under three different objectives:

- Support to all Application Cases to set up and operate MDO process
- Provide a final feedback on OCE implementation
- Assess the developments of AGILE4.0 project

This deliverable provides the main lessons learnt from the optimization set up and execution process across all the seven Application Cases.

2.2 AGILE 4.0 Application Cases

The ACs are representative of 3 main product development streams: production driven, certification driven and upgrade driven. A short recall of each AC goals is made below and more details can be found in [1], [2] and [3].

2.2.1 Application Case 1: Flap design optimization for noise reduction and optimal manufacture

This AC is part of the production stream and aims at bringing manufacturing in the aircraft MDO workflow. The AGILE 4.0 MDO framework will be used for the design on 2 different concepts (drop-hinge and Manta concept). The two different solutions are characterized by different impact on aircraft performance (e.g. mass, aerodynamic efficiency) and different manufacturing processes.
The objective is to have the ability to select the best flap to produce by trading performance vs manufacturing costs and manufacturability.

2.2.2 Application Case 2: Horizontal tail design optimization including uncertainties due to supply chain issues

This AC is part of the production stream and aims at accounting Supply Chain in the aircraft MDO workflow. The AGILE 4.0 MDO framework will be used for the design of a horizontal tail plane (HTP) made by different materials. The different solutions are characterized by different impact on aircraft performance (e.g. mass, aerodynamic efficiency), different manufacturing processes and different combination of supply chains.
The objective is to have the ability to select the best HTP to produce by trading performance vs manufacturing costs vs supply chain performance

Fig. 2 provides an overview of the two application cases of the production stream.

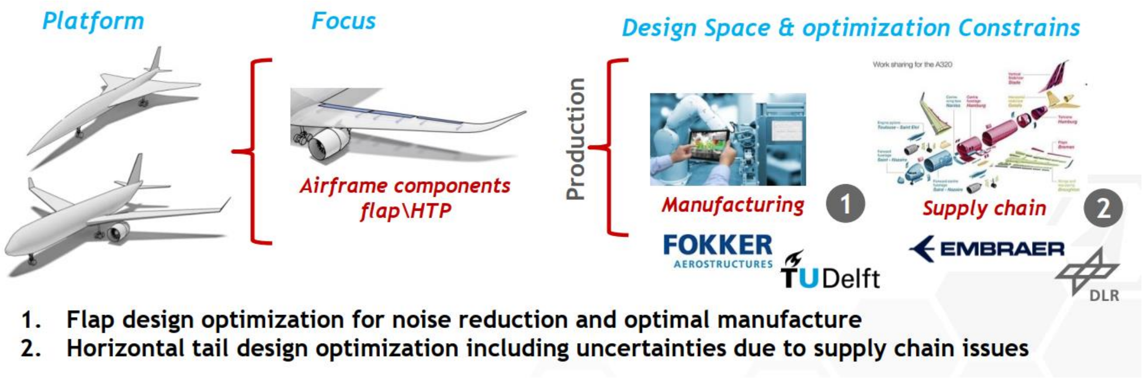


Fig. 2: Overview of production stream application cases

2.2.3 Application Case 3: Systems electrification

This AC is part of the certification stream and aims at accounting certification in the aircraft MDO workflow. The AGILE 4.0 MDO framework will be used for the design of a 19 PAX, regional turboprop aircraft with multiple on-board systems (OBS) architecture. These different solutions are characterized by increasing electrification with different impact on aircraft performance and on safety and reliability.
The objective is to have the ability to select the best OBS by trading performance vs certification time/cost.

2.2.4 Application Case 4: Maintenance Based Design

This AC is part of the certification stream and aims at accounting maintenance in the aircraft MDO workflow. The AGILE 4.0 MDO framework will be used for the design of a 19 PAX, regional turboprop aircraft with multiple OBS architecture, with similar TLAR as AC3. These different solutions are characterized by increasing electrification with different impact on aircraft performance and maintainability.
The objective is to have the ability to select the best OBS by trading performance vs maintenance time/cost.

2.2.5 Application Case 5: Virtual Airframe

This AC is part of the certification stream and aims at accounting certification in a UAV MDO workflow. The AGILE 4.0 MDO framework will be used for the design of a UAV with the integration of airframe and OBS certification constraints, specifically Electro-Magnetic Compatibility (EMC) and heat management constraints. The different solutions are characterized by different impact on aircraft performance and different certification criteria.
The objective is to have the ability to select the best UAV by trading performance vs certification performance.

Fig. 3 provides an overview of the three application cases of the certification stream.

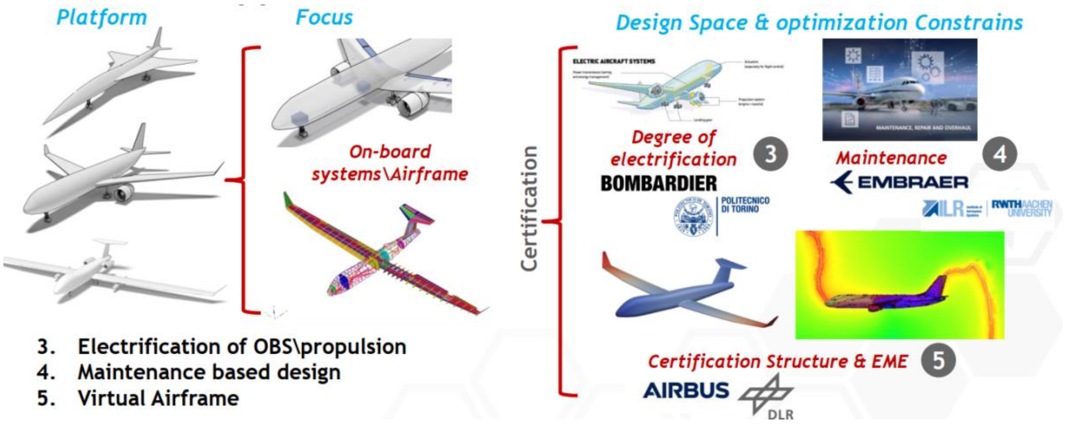


Fig. 3: Overview of certification stream application cases.

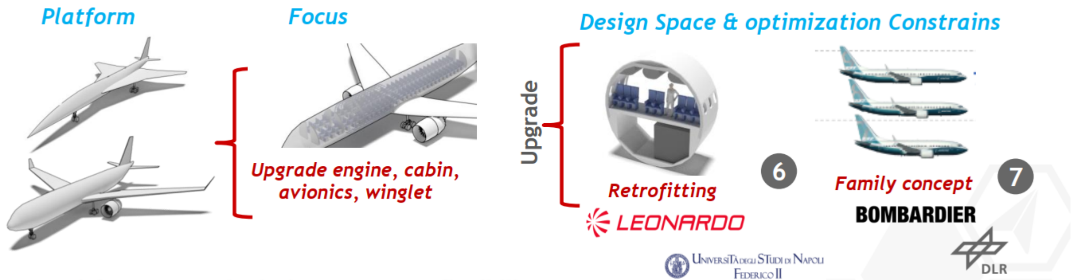
2.2.6 Application Case 6 Airframe upgrade design

This AC is part of the upgrade driven stream and aims at accounting retrofitting options in the aircraft MDO workflow. The AGILE 4.0 MDO framework will be used for the design on several retrofitting concepts (engine, OBS, winglet). The different solutions are characterized by different impact on aircraft performance (e.g. direct operating cost (DOC), emissions) and different retrofitting costs.
The objective is to have the ability to select the best retrofitting strategy to produce by trading DOC/emission vs retrofitting costs.

2.2.7 Application Case 7: Family concept design

This AC is part of the upgrade driven stream and aims at accounting commonality options in aircraft MDO workflow. The AGILE 4.0 MDO framework will be used for the design of 3 different aircraft with different commonality choices (wing, engine, Empennage). The different solutions are characterized by different impact on aircraft performance (e.g. mass, aerodynamic efficiency) and different commonality choices.
The objective is to have the ability to select the best family by trading performance vs commonality.

Fig. 4 provides an overview of the two application cases of the upgrade driven stream



6. **Airframe upgrade design vs costs vs flexibility**
7. **Architecture design for family**

→ Which upgrade should we perform? Cabin, Propulsion, avionics, airframe.
→ What is the more flexible architecture in a family context?

Fig. 4: Overview of upgrade driven stream application cases

2.3 AGILE 4.0 steps

The high-level representation of AGILE 4.0 approach is presented in Fig. 5 and summarized as follows:

- The AGILE 4.0 approach starts with the **Identification** step of system of interest. In this step, stakeholders and collection of their needs are conducted.
- Then, the **Specification** step is performed. Here, Concepts of Operations (ConOps) are elaborated to describe through scenarios how the system will operate during its life cycle and therefore to refine and validate stakeholder needs. Validated needs are then transformed into requirements.
- The next step concerns the **Architecting** phase. Requirements, produced in the preceding step, drive the system architecting and its development. Several potential solutions are defined by generating different system architectures made of different logical components, i.e. system components (e.g. engine, wing) that are not constrained to a particular technology.
- Then the **System Synthesis** is considered. In this step, conceptual designs are performed to derive potential and not optimized physical architectures of the System of Interest.
- Finally, the last step concerns the **Design & Optimization** phase. The various system physical architectures are finally designed and optimized through MDAO processes. Trade-off analyses are performed and decision-making techniques are adopted to eventually define the best solution.

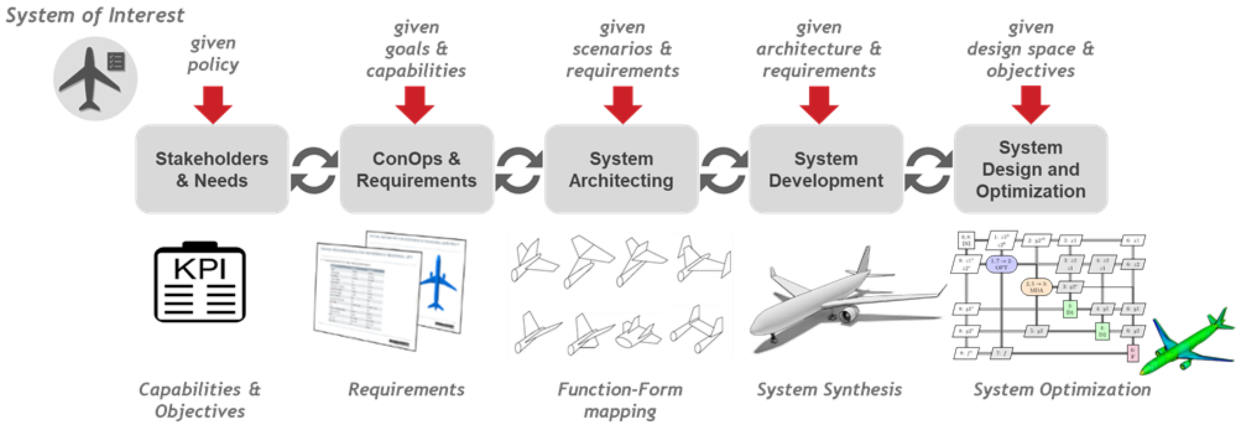


Fig. 5: Schema of the AGILE 4.0 steps.

As the lessons learn and best practices presented in the deliverable are related **Design & Optimization** phase, a more detailed presentation of the sub steps seems necessary for a better understanding of the lessons learnt.

As stated above, the Design and Optimization step includes all the activities related to the setup and execution of the simulation workflows.

2.3.1 Formulate simulation workflow

The workflow is composed of integrated multidisciplinary design competences, which are developed and implemented across various organizations. First, the design team needs to ensure the connection between the system models (e.g. representing system requirements or system architecture) and the MDAO workflow. This can be made in several ways.

2.3.1.1 Support in connecting the system models to the MDAO workflow

One of the functions of the *workflow generator component* is to support the connection between the system models (e.g. representing system requirements or system architecture) and the MDAO workflow. The system models have to be connected in a user-friendly and transparent way, such that the formulated workflow does not only represent the 'what' of the workflow, but also the 'why'. The connection between the workflow and the system models can be made by deriving the workflow tools from the means of compliances and linking requirements to the optimization and analysis variables.

In order to facilitate these connections and the workflow creation, the design competences are used in the simulation workflows are represented by their input and output files (in CPACS schema) that is then handle by a workflow generator KADMOS (Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System) [5] and MDAx [6].

2.3.2 Specify the MDAO architecture

The next step is the specification and application of the MDAO architecture. Once the design competences are properly defined, the input and output files are scanned and connections between the tools are automatically made. The integrator can specify the MDAO architecture that is automatically applied on the MDAO problem. Specifying the architecture consists of assigning problem roles to the different variables (e.g. objective, constraint, etc.) and deciding on the method to optimize or converge the MDAO problem (e.g. choosing the number of convergers, optimizers, partitions, etc.). The integrator can choose between predefined architectures (e.g. MDF, IDF, CO) or generate its own architecture. Once the workflow is fully formulated, it is exported to a workflow definition exchange format, like CMDOWS.

2.3.3 Visualize and inspect the MDAO process

Then the visualization and inspection of the generated workflow can be achieved. Once the workflow is formulated, it must be easy to visualize the workflow and to inspect whether all the connections between the different tools and the connections with the convergers and optimizers are generated as expected. KADMOS combined to VISTOMS (VISualiziaton TOol for MDO Systems) [7] and MDAx both provide the capability to visualize and inspect workflows.

2.3.4 Access to optimization capabilities (RSM, optimizer)

Within the AGILE4.0 project, *Surrogate Model Generator* (SMG), developed by NLR, is used to facilitate the creation of surrogate models, registration of this process and connection of the involved actors within collaborative MDAO studies. While specifying the competences to be used within an MDAO solution strategy, the user can indicate a specific surrogate model is required to represent the results of a pre-executed engineering service, e.g. to keep the run time low. In this case, SMG initiates the creation of a surrogate model using the principles of the AGILE development process, involving the competence specialist and a surrogate modelling specialist.

At the start of the project, another foreseen development was an optimization library create in order for the integrator to access to a selection of available optimizations methods provided by other partners and exposing their metadata to guide the selection

2.3.5 Execute workflow in a collaborative environment

At that stage, a Process Integration and Design Optimization (PIDO) component, here RCE [8], is required to execute disciplinary workflows. The executable workflows are directly imported from the *workflow generator component* (using CMDOWS), or manually set up by the user. The executable workflow integrates the different disciplinary tools, which are treated as black-boxes: only inputs and outputs are relevant for the component and the codes are not exposed. The disciplinary tools are installed locally or in servers. Different types of MDAO problems can be executed in the component, as basic multidisciplinary analysis, DOEs or full optimizations.

Another key aspect of the collaborative workflow derives from the collaborative design process. Since the different disciplinary tools can be hosted in different locations, executable workflows are usually distributed simulation workflows across multiple networks across multiple companies. In AGILE4.0, BRICS tool [9] is used as provides the mechanism for interconnecting PIDO environments – and hence multi-partner and distributed collaborative simulation workflows – in OCE. By providing data encryption services, BRICS supports protection of the data to be exchanged to and from the central data server in which the CPACS information is transferred between the disciplinary tools.

2.3.6 Produce trade off studies

This sub step aims at evaluating and comparing different potential design solutions by trading multiple design factors. The factors to consider in trade-off analyses depend on the use cases context and their objectives. These analyses deal with multiple domains as design, manufacturing, certification and maintenance. Examples of multi-domains trade-off analyses include fuel consumption vs. manufacturing cost, certification time vs. performance. A specific OCE component should be used that assess and compare the design solutions and shows them in a trade-space.

2.3.7 Post-process of the simulation workflow results

The post process sub step should rely on two different OCE components, not available at the beginning of the project:

- The *product visualization component* aims at inspecting the geometry of the aircraft. This component shall be able to process the information (e.g. aircraft parts, dimensions, locations) stored in the product data schema CPACS and represent it as a 3D model.
- The *report generator component* should enable a standardized output of key attributes of the investigated aircraft configuration and the display of the results of trade off analyses. The generated files (such as pdf report, figures and tables) should be put out to the OCE where they can be viewed, downloaded and stored.

2.4 Application Cases Lessons learnt

The lessons learned are summarized and analysed in accordance with the AGILE4.0 formalization steps presented earlier. It is important to note that the full implementation of the Operational Collaborative Environment (OCE) was still in development when the Application Cases began their Design & Optimization activities, so feedback from the integrators has been considered in the improved capabilities of subsequent OCE releases. Additional information on OCE achievements can be found in [9]

2.4.1 Formulate simulation workflow

During the early stages of the project, the focus was on producing state-of-the-art (SOTA) workflows as the first step of activity. As the project progressed into its second and third years, the objectives of each Application Case (AC) were refined, and the workflows were updated to include new design competencies and a renewed focus on optimization. The updated workflows took advantage of the enhanced capabilities of the Operational Collaborative Environment (OCE) as they were implemented, leading to several lessons being learned during this step

2.4.1.1 OCE related activities

- Connecting tool to CPACS

As previously identified in the AGILE project, creating a new design competence that is compliant with CPACS always requires a minimal amount of time. After the first year of activity, once the SOTA workflow was made operational, some design tools had to be added (such as the ASSESS tool from CONCORDIA) or adapted to better fit the target use case (such as the Certification Tool from ONERA). While some extensions to the CPACS data schema were anticipated in year 2, such as the extension of the OBS branch to include more detailed information, the use of “tool-specific” branch offered by CPACS was not an exception. In fact, the evolution of the CPACS schema is not always aligned with the task timeline, and partners often resort to using “tool-specific” branche to expose their connections until a new CPACS version is released.

- Connecting Design competences

In AGILE4.0, the integration of design competences in OCE is performed through the inputs and outputs of each tools that are stored as in- and outputs of CPACS files. When setting up the workflow for the first time, there is commonly a minimal amount of time to ensure that all the tools are mapped to the same reference CPACS, as, sometimes, the possible existence of different UID’s for the same branches between different in- and outputs of CPACS files would end up with the tools not be identified as coupled.

- Mixing different level of fidelity

Most of the ACs workflow of the project relied on design competences of various fidelity levels. In some cases, high fidelity tools were necessary in order to ensure an accurate prediction of the performance. One can think about aerodynamic drag prediction in AC3 and AC6, structural wing weight prediction in AC6 and AC7 or even LIE prediction in AC5. The challenge with using these tools was that they often required significant computation time, which can be incompatible with an optimization approach. However, this issue was resolved through the use of RSM (presented in 2.4.2)

2.4.1.2 Design team activities

- Work organisation

The team work was organized using the ***OCE landing environment***, the centralized environment where all end-users have access to, which allows management of AGILE4 use-cases and central databases containing reusable models that are shared across use-cases and design studies. In the environment, each application project is represented by a use-case projects where partners can perform different design studies. A design study contains the process template to setup a design problem, and evaluate the design by executing MDAO workflows composed of available disciplinary tools. The environment allowed to specify the role and the task scheduling of each partners and was considered as satisfactory by all the ACs.

- Design competences selection

One key lesson learnt of the project is the impact of the design competences on the exploration of the design domain during the optimization studies. Given that the project aims to encompass multiple architectural choices for various aeronautical domains, it is important to carefully consider the design competencies that are selected. For example, if the architectural design space includes a variety of propulsion solutions, the MDAO workflow should have the ability to evaluate all the architectural options. If the pre-selected design competence is unable to compute a certain architecture, the optimization space becomes limited. To address this potential limitation of optimization exploration, the development of WP3 proposed an evolution of A4F to solve this issue.

2.4.2 Specify the MDAO architecture

One specificity of the project is that all the applications cases have to consider multi objectives optimization (at least two) and problems involving mixed – variables (and in some case only categorical ones).
In addition, it appeared that when workflows were getting more complex, ACs partners did not aim directly towards optimization but usually wanted to first test the workflow, analyse the results obtained by each design competence and the overall behaviour induced by the coupling process. In other words, some intermediate problems need to be formulated first, with increasing complexity, leading to the usual following steps: unconverged MDA, converged MDA and DOE

2.4.2.1 OCE related activities

Classical mono level formulations are within the framework, like MDF and IDF (in KADMOS) as well as ad-hoc formulation (in MDAx). All the ACs select MDF formulations for several reasons. First, as written in the preceding paragraph, it relies on the MDA which needed to be operated to assess the behaviour of the workflow. Secondly, in the former AGILE project, decoupled formulation, like IDF of ATC had been evaluated but it was found at that main difficulty was to define the range for coupling variables between design competences (that needed to be transferred as design variables for the optimization problem). In many cases, inaccurate settings led to tools crashing when the workflow was operated.

2.4.2.2 Design team activities

As two different tools were implemented in OCE to support the specification and application of the MDAO architecture. Depending of the complexity and specificities of the workflow to be set up and the number of involved design competences, each AC integrator was able to select the most convenient one. Some enhancements were implemented during the course of the project, to ease and extend the use of such tools. For instance, KADMOS offers now the capability to partition the workflow, leading to a reduction in the execution time of one iteration.

2.4.3 Visualize and inspect the MDAO process

This step mainly aims at checking the workflow obtained before the execution step and ensuring that all the inconsistencies are clearly identified and solved.

2.4.3.1 OCE related activities

Both KADMOS and MDAx comes with its own user interface to visualize and inspect workflows.

2.4.3.2 Design team activities

- Work organisation

Like for other techno implemented in OCE, during design studies, these tools helped reducing the development time enabling a quicker and better visualization of the links between the different tools and the connections with the converges and optimizers. They were considered satisfactory by all the ACs.

2.4.4 Access to optimization capabilities (RSM, optimizer)

This step is rather important in collaborative MDAO studies as it consists to facilitate the access and the connection of the partners to a set of dedicated tools and algorithms requested by complexity of the problems. In AGILE 4.0, the wide variety of Application Case has allowed to test and benchmark different approaches.

2.4.4.1 OCE related activities

- Surrogate Model

As stated earlier, extensive use of RSM was made necessary to reduce computational time of MDO workflow by replacing the costly competence. At least four different approaches have been applied depending on the available level of RSM expertise in each AC

- First approach was to replace a costly competence (remotely called) with a RSM, built off line and directly implemented in the owner's workflow. This approach reduced the overall computational time, but it required that the tool owner either have expertise in RSM handling, which is not always the case or desired, or be willing to develop that expertise. In addition, some specific RSM, like multi fidelity ones or mixed variables ones are not widely spread among partners.
- Second approach was to directly replace the costly competence (remotely called) with a RSM, built off line and directly implemented in the integrator's workflow. This approach appears to be more reliable, as it eliminates the need for remote calls to the competence. However, it has two drawbacks. The first one is that RSM tool needs to be installed locally at the integrator site (and this not always possible -unless it is open -source- and the second one is that the partners owning the tools is no longer involved in the workflow execution.
- Third approach, evaluated in most ACs, was to replace the costly competence (remotely called) with a RSM, built off line and now implemented on the RSM's expert workflow. This approach was mainly applied with SMT toolbox models that were stored, as design competences, on ONERA's computer. It solves the first drawback of the preceding approach (RSM tool remains on RSM expert's site) but not the second one.
- A last approach relies on SMR technology that facilitate the creation of surrogate models, their registration for use in the workflows, and their access. A key enhancement of AGILE 4.0 was the ability to smoothly connect SMR to different surrogate modelling competences providers in a transparent way from the end-user perspective. As an example, ONERA 's surrogate modelling competences relies on SMT Toolbox [10] and are made accessible "as a service" to SMR through WhatsOpt [11], a web application supporting MDAO collaborative activities. This solved most of the drawbacks identified earlier while easing all the RSM building steps. This latest approach was successfully demonstrated in Application Case 3.

- Optimization algorithm

As all the ACs had to address multi-objective optimization problems with mixed variables, the optimization algorithms currently available through RCE were not entirely suitable (direct application of genetic algorithms would result in an excessively large number of evaluations). Only a few partners, such as ONERA, NLR, or UNINA, were able to provide gradient-free algorithms capable of solving these types of optimization problems. At least four different approaches have been applied:

- The first approach consisted in using an adequate optimization algorithm located on the integrator's site. But it means that the integrator has also an expertise in optimization and in AGILE4.0, only UNINA could apply this approach.
- The second approach consisted in considering the MDA workflow as a whole that can be called remotely like any design competence from an RCE specific workflow located in the optimizer owner's premises. Despite being successfully applied in multiple ACs, this approach also suffers from a drawback: the master of the workflow is now the optimizer's expert an no longer the integrator (even though he still in control of the MDA)

Two different tracks have been explored in parallel to give back the control to the integrator

- The first idea was to create an optimization library in order for the integrator to access to a selection of available optimizations methods provided by other partners and exposing their metadata to guide the selection. In a pre-process phase, all the optimization algorithm of the list should have been made compatible with the RCE optimization API to ease their integration in the workflows. Unluckily, this last step, even if feasible, would have led to adaptations of the RCE API incompatible with RCE team involvement in the project.

- The second idea was applied the optimization process not on the design workflow but directly on the architectural choices that is connected to the RCE workflow through ADORE an MultiLinq technos. This approach was successfully demonstrated in AC7. It allows the integrator to use a wider range of optimizers, either called locally or remotely

2.4.4.2 Design team activities

- Work organization

One of the complexities of the ACs was the identification of the best suited approach for optimization especially considering the wide range of computational time (from 30 seconds up to one hour for the MDA) and problem dimension (from 2 variables to almost 100). As the optimization problem were partially adapted in the frame of the project, the optimizer's provider had to re organize their involvement per AC depending on where their capabilities suited best. But this aspect was anticipated with available man power in the support activities of WP3.

2.4.5 Execute workflow in a collaborative environment

A specificity of AGILE4.0 is that all ACs extensively run in the for 1 year with multiple approaches, from MDA to complete optimization. Regarding the execution perspective, the impact of parameters could therefore be evaluated:

- the MDA computational time ranging from 30 seconds to 1 hours,
- the number of involved partners ranging from 1 up to 6,
- the localization of partners, either spread around Europe or also involving Canadian partners,
- the number of tools layer called by the workflow, ranging from one (tools on the integrator's, premises) up to three (optimizer's location, integrator' s location and partners' s location).

In AGILE 4.0, this wide variety of executable workflows has allowed to extend the lessons learnt from the previous AGILE project.

2.4.5.1 OCE related activities

- Incremental complexity for execution of workflow

As previously mentioned, when workflows became more complex, the partners in the ACs didn't immediately move towards optimization. Instead, they usually first tested the workflow, analysed the results produced by each design competence, and evaluated the overall behaviour induced by the coupling process. To do this, intermediate problems such as MDA and DOE were carried out before optimization. For example, in AC1 and AC3, conducting the DOE helped identify unusual behaviour and resolve it before proceeding to the optimization step

This process also revealed robustness issues. Whenever a partner encountered an internet connection problem or a license access issue, the workflow would crash, resulting in the loss of the current MDA evaluation. To address this, a new version of BRICS was released during WP3 that added the capability to handle multiple retries for calls to design competences, with a buffer time between each retry, in case they were not reachable on the first attempt. This new version was distributed to all partners and greatly reduced the number of workflow crashes

2.4.5.2 Design team activities

- Design campaign organisation

Each design campaign had to be carefully scheduled to ensure the availability of all partners. Additionally, when a Canadian partner was involved, the workflow could only be started in the afternoon in Europe. Due to the nature of multi-objective optimization, many evaluations were needed, but only fewer than 20 evaluations could be completed in one afternoon if the MDA took more than 15 minutes to converge

As a result, surrogate-based optimization was selected for all ACs. Some ACs used an offline surrogate-based optimization, where a sufficient DOE was run first in multiple campaigns. Then, optimization was conducted offline to identify the Pareto front using an RSM based on the DOE database (like in AC1 and AC6). The other approach involved a smaller initial DOE and then an enrichment process that directly called the workflow.

Both approaches allowed for handling of any stopped or crashed workflows because they relied on a database of computed points to predict the next point.

2.4.6 Produce trade off studies

The ability to produce trade off studies, between two different domains was a new feature in AGILE4.0. The aim is to evaluate and compare different potential design solutions by trading multiple design variables. Depending on the AC, these analyses should deal with multiple domains as design, manufacturing, certification and maintenance. Examples of multi-domains trade-off analyses include fuel consumption vs. manufacturing cost, certification time vs. performance.

2.4.6.1 OCE related activities

As all ACs managed to achieve multi objective optimization covering two different domains. Depending on the AC, more than two objectives were sometimes considered (up to 5). Whenever this occurred, it meant that more than two objectives could belong to one domain and needed to be aggregated in a single value.
A specific techno, VALORISE, was introduced in OCE to achieve this capability, relying on *utility functions* in order to compares the design solutions and to show them in a two-dimension trade-space.

2.4.6.2 Design team activities

The selection of trade-off objectives needed to be made early in the project, as it had a significant impact on the optimization problem that needed to be solved. However, due to the limited information about the available design competences and possible architectures, the trade-off parameters were sometimes defined later in the project timeline. To mitigate this, some of the Application Cases (ACs) chose to include multiple objectives in the optimization step, which allowed stakeholders to adjust the utility function used for trade-off. This approach, however, made the optimization process more complex
Within WP3 development activities, this possible limitation of the optimization exploration was addressed and a proposed evolution of A4F aimed to solve it through the introduction of the concept of trade-off scenarios.

2.4.7 Post-process of the simulation workflow results

At this stage, the objective is to efficiently enable all partners to analyze the results from the optimization process and make decisions accordingly. Here, the results can be optimization history, system performance indicators and system optimal design with, for instance, aircraft geometry or visualization of the components placement

2.4.7.1 OCE related activities

As all information regarding the aircraft are stored in a CPACS file, one can process the information (e.g. aircraft parts, dimensions, locations) stored in this CPACS to represent it as a 3D model using specific viewer like TIGL. Nevertheless, information related to other domain (like manufacturing or supply chain) did not have specific viewer development connected to OCE and partners had to rely on in house scripts or tools
In addition, another feature expected from OCE was a *report generator component* that should have enabled a standardized output of key attributes of the investigated aircraft configuration and the display of the results of trade off analyses (using CPACS data). Unluckily, this capability development was not finalized during the project timeline.
No specific tool was developed regarding the automation of optimization history in OCE.

2.4.7.2 Design team activities

This step is crucial in the design and optimization process as the entire team needs to be able to analyze the results, both for overall performance and design, as well as the results from each individual discipline tool. The lack of automation in OCE, resulted in the integrator developing their own analysis tools, mainly in the form of scripts, and visualization tools, mainly using TIGL. The optimization experts also suggested different visualization approaches to help understand the optimization behavior. As a result, the need for a unified report generator was identified.

2.5 Best practices

The best practices for design and optimization of highly collaborative workflows have been summarized in accordance with the AGILE4.0 formalization steps. These best practices aim to provide guidance for design teams and identify potential ideas for inclusion in an operational environment implementation roadmap.

2.5.1 Formulate simulation workflow

2.5.1.1 Operational environment

Several improvements have been made to the framework of AGILE 4.0 to simplify and link this step to the previous ones in a MBSE approach. For example, the RVF technology allows for the direct formulation of MDO workflows from requirements, thus ensuring that all necessary design competences are selected. However, some additional developments have been identified during the WP3 activities to ensure the consistency of the workflow with the architectural design space and the early identification of trade-off scenarios.
All these evolutions have been documented in the deliverable D3.3.

2.5.1.2 Design team

This step is the one that might most impact the overall capability of the team to achieve the goals of the collaborative optimization as any inaccuracy at this stage will impact the optimization either by limiting the scope of the studies or delaying the complete optimization execution. Therefore, several good practices can be identified:

- Tools preparation
    - Anticipate the workload for CPACS compliancy of new tools
    - Establish a baseline CPACS file for all design specialists to test their tools
- Consistency with architectural design space
    - Ensure that the selected tools are compliant with the architectural design space
    - Consider creating a tools catalogue for design competences (existing or to be added)
- Trade offs scenarios
    - Verify that the trade offs scenario are clearly define

2.5.2 Specify the MDAO architecture

2.5.2.1 OCE related activities

The currently available tools in OCE, namely KADMOS and MDAx; effectively meet the main objective of this step, which is to generate a variety of MDO workflows from MDA.
However, some improvements were identified during the WP3 activities. Firstly, many of the ACs ended up running MDF workflows even though the MDA inner convergence loop could increase the optimization time. Alternative formulations, such as the EGMDO formulation [12]) could be automated to offer advantages in terms of the number of calls to each discipline while providing a relatively low number of iterations. Secondly, exploration and implementation of uncertainty quantification and optimization under uncertainties should be pursued, as they provide the benefit of delivering optimal, robust, and reliable designs.

2.5.2.2 Design team activities

At this stage, the good practices inherited from the AGILE project are already being applied, but one additional practice can be identified. This best practice suggests that the team should not immediately aim to tackle the most complex optimization problem, but should instead start by setting up and solving problems of increasing complexity, including MDA, DOE, and even offline black-box optimization using the DOE database, to fine-tune the optimizer parameters. The team could also consider partially converged, simpler optimizations as an option.

2.5.3 Visualize and inspect the MDAO process

2.5.3.1 OCE related activities

No improvements are deemed necessary for workflow visualizations as the current tools, KADMOS and MDAx, meet the expectations and requirements.

2.5.3.2 Design team activities

At this stage, the only recommendation for the design team is to take advantage of the technology visualization capabilities. The team should hold regular meetings, even when not all the tools are available, to discuss the status of the workflow and visualize the connections between the design competences using these visualization capabilities. This will help the team to assess the workflow and ensure that it is on track.

2.5.4 Access to optimization capabilities (RSM, optimizer)

2.5.4.1 OCE related activities

Several improvements have been made to the RSM in the framework of AGILE4.0 to simplify and automate their use. For instance, SMR now has the ability to connect OCE to different surrogate modelling competence providers in a transparent way from the user's perspective. However, some further developments have been identified. For example, in some cases, several tools of different fidelities for the same discipline were available, and automating the process of building mixed-fidelity models would be a useful improvement.

As for optimization algorithms, optimizers capable of handling multi-objective and mixed-variable problems are not typically included in PIDO frameworks like RCE. Developing an optimization library concept that would allow workflow integrators to access other partners' optimizers through the RCE API would greatly facilitate the execution step.

2.5.4.2 Design team activities

At this step, the focus should be on clearly identifying the design team's needs with regards to RSM and optimizers:

- RSM need
    - Identify costly competences and / or competences that are difficult to call remotely
    - Work with an RSM expert to identify the most appropriate RSM choice
    - Anticipate the workload to create the necessary database and select RSM parameters
- Optimizer selection
    - Specify the characteristics of the optimization problem (number and type of variables, number of objectives and constraints, average evaluation time, etc.)
    - Anticipate the workload to connect the optimizer to the workflow

2.5.5 Execute workflow in a collaborative environment

2.5.5.1 OCE related activities

Several improvements have been made to ease the execution of workflows in AGILE4.0. For example, the enhanced version of BRICS has reduced the number of crashes in all the ACs. However, some workflows still experience unexpected stop when running for more than 10 hours, so further development of OCE technology related to this step should aim to minimize workflow crashes and make the restart procedures easier.

2.5.5.2 Design team activities

This step is the most time-consuming of the design and optimization activities. Several best practices have been established based on the AGILE4.0 experience:

- Plan the design campaign(s) well in advance with a buffer time in order to ensure that all partners are be available

- When the design campaign is launched, set up a specific group, with all partners, in a team chat app and use it to keep all partners informed about the status of the workflow, especially when the settings of the workflow are new
- During the optimization, each partner should periodically check the outputs of the tools to ensure consistency

2.5.6 Produce trade off studies

2.5.6.1 OCE related activities

In this step, improvements have been made at the OCE level to facilitate the trade-off analysis of the workflow results. Tools like VALORISE provide a method for comparing design solutions and displaying them in a two-dimensional trade space. The next evolution could address the uncertainty associated with the choice of utility functions and weights in order to provide stakeholders with a more robust solution.

2.5.6.2 Design team activities

As the VALORISE tool was implemented at the end of the project, no best practices have been established yet.

2.5.7 Post-process of the simulation workflow results

2.5.7.1 OCE related activities

This step is the one where many improvements are still to be implemented in the OCE framework. The first one should target the introduction of the report generator that would display in an automated way the results of trade off analyses. The second type of improvement would be to facilitate the connection to application case specific viewers especially when considering information related to other domain than design (like manufacturing or supply chain)

2.5.7.2 Design team activities

As this step deals with the overall analysis of the results, several best practices have been identified:

- Agree in advance among team members on the quantities of interest to be monitored (in addition to optimization variables and objectives)
- Anticipate the workload of creating custom scripts for analysis, if necessary
- Utilize the report generator capabilities (if available) to prepare and distribute the main results to stakeholders of the application case.

3 CONCLUSION AND OUTLOOK

In this deliverable D3.2, the main lessons learned from the optimization setup and execution process across all application cases (ACs) of the AGILE 4.0 project are discussed in detail. The report provides a recap of the project application cases as well as an overview of the AGILE 4.0 steps with a specific focus on the design and optimization step. A systematic analysis of the lessons learned was performed from both the implementation and design team perspectives. Furthermore, it highlights best practices for setting up and executing challenging collaborative multidisciplinary design optimization (MDO) workflow

Throughout the different ACs, a diverse range of optimization problems were tackled, each with its own set of unique challenges. The extensive analysis of the feedback enabled an assessment of the achievements of the AGILE 4.0 MBSE framework and the identification of bottlenecks in some parts of the design and optimization step that could be further improved in future projects

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