31st Congress of the International Council of the Aeronautical Sciences
Belo Horizonte, Brazil; September 09-14, 2018

COLLABORATIVE OPEN SOURCE AIRCRAFT DESIGN FRAMEWORK FOR EDUCATION - AGILE ACADEMY INITIATIVES AND RESULTS

Pierluigi Della Vecchia *, Benedikt Aigner, Imco van Gent ***, Pier Davide Ciampa **** , Prajwal Shiva Prakasha ****;**
University of Naples - Italy *, RWTH Aachen University, Germany, TU Delft - The Netherlands**, German Aerospace Center DLR – Germany******

Keywords: *Aircraft Design, MDO, Academic Research, Collaborative Design*

Abstract

AGILE Project is a 3rd generation Aircraft Design Optimization project involving heterogeneous teams of expert across Industry, Academy and Research organization. The establishment of effective collaborative design methodologies is currently acknowledged as the key enabler for future product development processes. At the same time, the need to introduce collaborative design techniques within educational activities is also well recognized by the Academic, Research and Industrial communities. AGILE project supported by European Commission's H2020 Programme, is setting the "AGILE Paradigm", a conceptual framework which contains all the elements to implement a multidisciplinary collaborative design network and several open source elements to implement and use in academic collaborations. The AGILE Academy initiative is conceived to infuse into the Academic organizations and educational environments the "AGILE Paradigm", and make available all the technologies developed within the AGILE Project, which support the implementation of such a Paradigm. This paper focus is on the inception, approach and results of the AGILE Academy participants from several universities around the world.

1 Introduction

The AGILE EU Project [1] is dedicated to the development of distributed multidisciplinary optimization methodology. The project is based on the key technologies developed over the last 10 years in the DLR: such as, for example, a common data format CPACS [2] and RCE [3] environment. The main purpose of AGILE project is to reduce by 20% the time of the convergence process in the aircraft optimization and by 40% for the multidisciplinary optimization in a team of various experts by the end of 2018.

AGILE ACADEMY Activities: AGILE ACADEMY consists of a series of activities carried out in collaboration with the Academic institutions. Such activities will support educational activities, such as student's thesis and University workshops, in order to promote and to make available the AGILE technologies to the entire Academic and research community [4]. Two main activities are proposed:

Phase 1 - AGILE Incubator: One team of distributed students, collaboratively working on a common aircraft design task. Focused within the AGILE EU project partner community.

Phase 2 - AGILE Challenge: multiple teams of students, collaboratively working and competing on a single (or multiple) design task(s). Focused multiple universities and research organization across the globe.

2. The AGILE Paradigm

Modeling framework for full MDO involving several disciplinary modules and heterogeneous teams for a complete aircraft development is still an open challenge. As pointed out in a workshop arranged by the National Science Foundation in 2011 [6], during the last decade the MDO community has shifted its focus, and 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 recent workshop which was held by the ICAS in 2015 on Complex Systems Integration [7] has highlighted the necessity of novel methodology which could encapsulate knowledge and skills to be able to manage the increasing design complexities. Such formalization towards "modeling knowledge" is addressed by Zhang [8] as the next step necessary to the evolution of aeronautical complex systems. The authors have identified that major obstacles in the current generation of MDO systems are largely related to the efforts required to setup complex collaborative frameworks. Ciampa et al. [9] quantified that 60 to 80% of the project time might be necessary to setup such complex processes. Many of the above-mentioned challenges are addressed in the AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) EU funded H2020 research project, coordinated by the German Aerospace Center (DLR). The AGILE project developed the next generation of aircraft MDO processes that target significant reductions in aircraft development costs and time to market, leading to more cost-effective and greener aircraft solutions. AGILE has formulated a novel design methodology, the so called "AGILE Paradigm", accelerating the deployment of collaborative, large-scale design and optimization frameworks. The MDO framework focused into a) setup phase, b) operational phase and c) solution phase as shown in Fig. 1. The abstraction reduces over the design and optimization process, as the knowledge increases

The goal of the AGILE framework was to make following improvements in the three phases of MDO as shown in Fig. 1 :

• Accelerate the setup and the deployment of distributed, cross-organizational MDO processes

• Support the collaborative operation of design systems: integrate specialists and tools

• Exploit the latest technologies in collaborative design and optimization

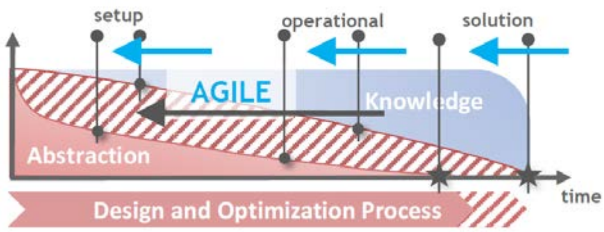

Fig. 1. AGILE main goals.

The process architecture of AGILE framework which will be used for agile academy. The AGILE Paradigm addresses the setup and the operation of MDO systems delivering an optimal solution for a given optimization problem. The process architecture tested during the AGILE project for 8 aircraft configurations, 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 process. A schematic on the major clusters of activities faced by the development is provided in Fig. 2, followed by an overall description for each of the phases.

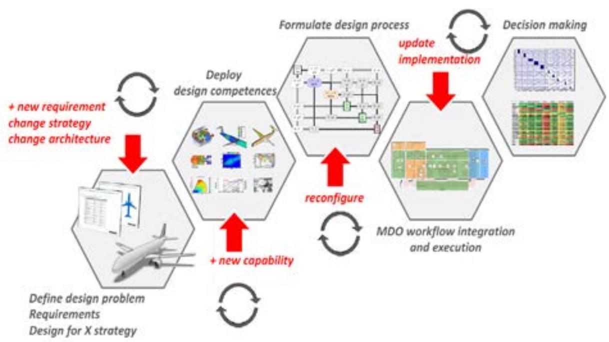

Fig. 2. AGILE development phases

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), design for electric certification and operational changes of the novel propulsion systems and the selection of a certain products' architecture (e.g. an aircraft configuration changes). 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 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. This phase is where academic partners will map the disciplinary module inputs and outputs to common standard data model (expanded CPACS) and prepare the tools to enable quick adaptation for AGILE framework. These provide the interfaces to the precedent and to the following phases.

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 embed interdisciplinary coupling in the hybrid electric aircraft, new aircraft design methods, 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. Most of this task was automatic during AGILE project and well tested.

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 trades pace).

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 (certification or thermal constraints or insulation), leading to additional competences or analysis modules to be added, or to a reconfiguration of the design process and to an update 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 interactions within and between the multiple phases. AGILE framework methodology will enable this reconfiguration quickly using the five-step approach as per the detailed literature explained by Ciampa et all 2018 [11] van Gent et all 2017 [10] and Ciampa et al 2017 [12].

3. AGILE Open Source Elements

The AGILE paradigm consisting of key elements a) Knowledge Architecture which formalizes the overall product development process as a hierarchical layered-structured process and b) A collaborative Architecture which formalizes the collaborative development process and enables cross organizational and cross the nation integration of distributed design competences of the project partners. In van Gent et alii [5] many information on knowledge architecture are provided, consisting of three hierarchical layers: development Process layer, Automated Design Layer, Design competence

Layer and a fourth layer transverse to all other layers is the Data and Schema Layer. Ref. [12] provides more information on Collaborative architecture, consisting of participating agents such as customer, architect, integrator competence specialist and collaborative engineer. The developments during the AGILE projects which were part of Knowledge architecture and Collaborative Architecture will be used in Macbeth. The enablers are PIDO environment such as RCE [13] , BRICS [14] which provides technology for interconnecting PIDO environments, 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) [15], the Data is handled with Central Data Schema CPACS, The generation and manipulation of the MDO architecture is provided by KADMOS (Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System) [16] and VISTOMS - VISualization TOol for MDO Systems [17], Additionally, extensive visualization techniques , supporting all the participative agents' needs, in the decision making, developed during AGILE and Idealism, ATLAS projects will be used.

3. The AGILE Academy

The AGILE Academy supports educational activities, such as student's thesis and University workshops, to promote the AGILE technologies and make them available to a wider MDO community. Two main activities have been realized (see Fig. 3): AGILE Academy Incubator and AGILE Academy Challenge.

As direct impact to the project, the AGILE Academy initiative provides a step towards the setup of the AGILE Open MDO Test Suite that will be disseminated at the end of the project. The training and teaching materials assembled during the AGILE Academy, will provide the basic module for teaching activities related to the dissemination of the "AGILE Paradigm" [1], both for industry, research centers and academia. Both elements will contribute to establish the AGILE Paradigm as a new collaborative development methodology, and to exploit the project's results beyond the duration of the AGILE Project. Several case studies tested by AGILE consortium using AGILE Paradigm, conventional civil aircraft and novel BWB aircraft design experiences were made available to the students during the course of Agile academy.

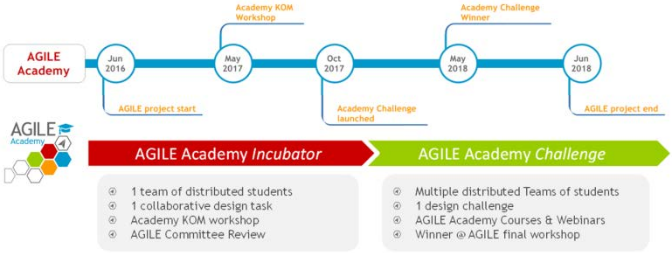

Fig. 3 AGILE Academy timeline

4. The Incubator Phase

Target Group: Academic Organizations **<u>within AGILE Consortium</u>**. Final year students, thesis oriented, 1-2 students per organization: TUD, RWTH, POLITO, UNINA

General Initiative Setup: Independent Thesis works are carried out at Universities, with the aim to develop\extend any of the in-house design capabilities. The developed capabilities are applied to independent use cases, defined by the Universities and not necessarily connected to AGILE EU project.

In addition a **Collaborative MDO application**, which makes use of the "**AGILE Paradigm**", will be performed by the team composed by the distributed students. The capabilities developed during the independent works will be integrated into a collaborative design and optimization exercise. Complementarity in the roles and tools have to be discussed from the beginning and may reflect the AGILE competence distribution. Such application will be limited in time and scope, and it is part of first dissemination activities of the AGILE related Concepts.

A 2 days **<u>AGILE workshop</u>** was hosted by DLR Hamburg in May 2017 at the beginning of the Thesis works to have an introduction on the "AGILE Paradigm" and its components. The team successfully brainstormed how to being their thesis and tools developed together with the AGILE open source framework. Three-day workshop also led to first preliminary run of framework (Fig. 4), additional webinars are arranged successively on monthly basis to support the students' team with respect to the test case and AGILE framework.

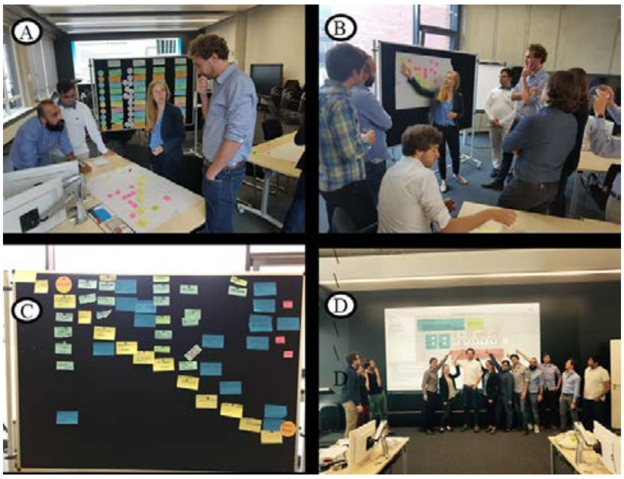

Fig. 4 AGILE Academy workshop in May 2017. Fig A) Students brainstorming on their thesis tools, B) Students presenting their initial workflow, C) Academy Framework workflow, D) Preliminary Workflow implemented in AGILE framework: Students pointing towards individual developed tools in workflow.

Use case:

Narrow Body 150 Pax TLAR and resulting aircraft may be used as reference, with technologies enhancements (e.g. hybrid electric version).

Link to the AGILE Eco-system elements:

In this first cycle of the AGILE Academy initiative, the following components of the AGILE environment will be distributed to the students' team for Educational purpose:

- Product model: the lower level of the AGILE Architecture → CPACS and tools
- Simulation workflow: mid-level → workflows manager, and MDO process representation
- Collaborative Architecture: cross-network implementation
- Disciplinary Competences: if required, a sub-set of competence available within the AGILE Consortium may be available for the completeness of the integration study.
- Visualization libraries
- IT support (e.g. tools server, etc.)

AGILE Academy Incubator Stage Workflow Formulation

The team decided to create an MDA analysis for conventional narrow body Aircraft with 150 Pax. The geographically distributed students brought in their disciplinary analysis together using AGILE framework (see Fig. 5).

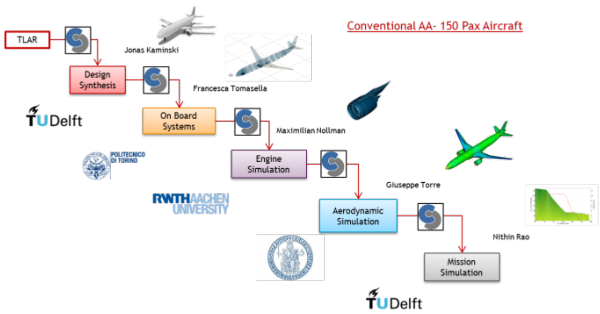

Fig. 5 Collaborative MDA framework, AGILE Academy

The workflow formulation was translated to DLR MDO framework RCE. Each block you see in Fig. 6 is a specific BRICS call (DLR: Initial Design, POLITO: On Board Systems, RWTH: Engine, UNINA: Aero, DLR: Mission simulation). BRICS is the software developed to collaborate across heterogeneous cross organization network. The University or research institute associated with the BRICS Call will run their respective disciplinary model or tool. The IT schema of the BRICS call is shown in Fig. 7.

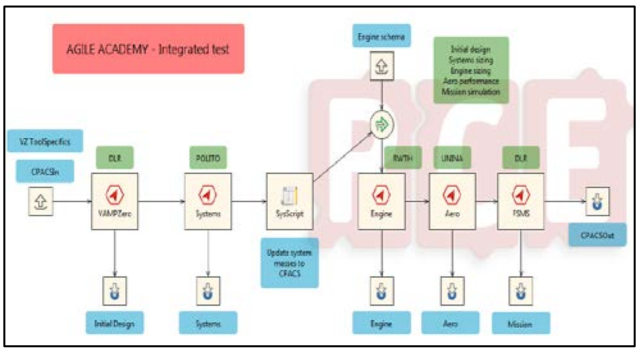

Fig. 6 Workflow in RCE Framework

Results

The team run the workflow as shown in Fig. 5 and Fig. 6. The results are as per the **Error! Reference source not found.** below.

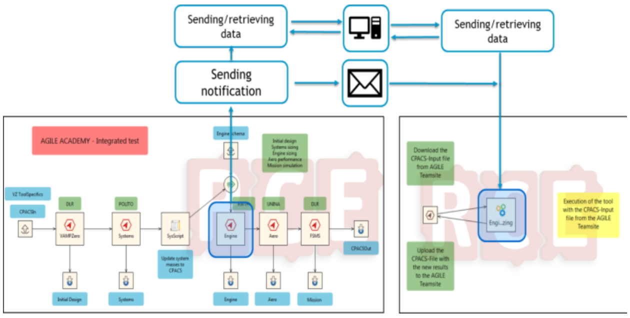

Fig. 7 Agile Academy cross organization data handling through BRICS, RCE and common central aircraft data Schema CPACS (www.cpace.de)

The team with limited time available successfully collaborated, designed aircraft and understood the collaborative paradigm, main results summarized in Fig. 8. Thus with more confidence in the framework, the challenge was expanded outside agile consortium.

Parameters	Empirical	Collaborative higher Fidelity	Difference
MOEM(kg)	49289	47550	-1738
Systems' Mass (kg)	12000	10261	-1436
Fuel Mass(kg)	11882	13318	1669
Payload Mass(kg)	13550	13550	0
MTOM(kg)	74720	74419	-301
Systems' Power Consumption	None	Systems' Shaft Power Systems' Bleed air	
Engine Performance	MaxThrust	Maps-Altitude, Mach, Thrust, Fuel flow rate	
Aero Performance	Mach,Re,Angle of Yaw, Angle of attack	Maps-Drag polar, moment coefficients	

Fig. 8 Academy Incubator workflow run and results

5. The Challenge Phase

The AGILE Challenge open for universities and research centers outside the AGILE project consortium, with the aim to disseminate the "AGILE Paradigm". The initiative targets the integration of the "AGILE Paradigm" using lectures, projects, and other possible academic activities at the universities participating in the AGILE Challenge. The initiative has been promoted on the AGILE website, as well as during international conferences and meetings, reaching attention in several worldwide distributed organizations.

The main numbers of the AGILE Academy Challenge are summarized in Table I. A total number of 36 participants from 15 organizations, coming from 4 different continents have been registered to the challenge (see Table I). The participants have been assembled in three cross-teams to compete in three different tasks. The three teams are assembled as follows:

- **Team 1**: University Carlos II of Madrid, University of Tokyo, RMIT University, Chinese Aeronautics Establishment
- **Team 2**: RWTH Aachen University, Polytechnic of Milan, University of Southampton, General Aeronautics India, IRT SystemX
- **Team 3**: ISAE Toulouse, ONERA, University of Michigan, Concordia University, University of PISA

The three tasks are identical for all teams and are listed below:

- TASK A – Assemble one multidisciplinary workflow per team.
- TASK B – Support collaboration with AGILE paradigm enablers for MDO.
- TASK C – Perform optimization through surrogate models.

Table I: AGILE Academy Challenge numbers

AGILE Academy Challenge	
Participants	36
Organization	15
Continents	4
Topics	All aircraft aeronautics disciplines
Teams	3
Supervisors	10

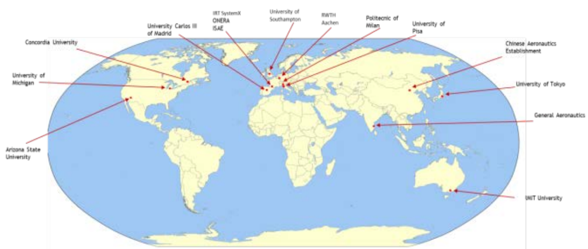

Figure 1 : The AGILE Academy Challenge "World"

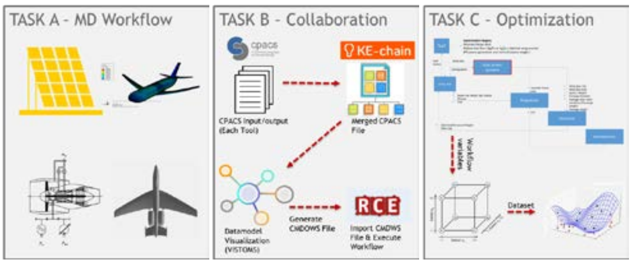

Figure 2 : AGILE Academy Challenge Tasks

5.1. TASK A

The main objective of task A was to introduce participants to the collaborative remote multidisciplinary aircraft design. The three teams were asked to assemble their own MDO workflow to design an aircraft, based on the same Top-Level Aircraft Requirements (TLAR). Many components of the AGILE environment have been distributed to the students to accomplish the task: *i) CPACS* as a central common data exchange format, *ii) RCE environment*, to have a collaborative design chain and *iii) BRICS* as a service to enable connecting design competence across organization.

The aircraft baseline has been initialized (based on TLAR) by the AGILE consortium and distributed to the teams in the CPACS format as a starting point for their own investigations.

The use case is a conventional (wing-tube) medium range transport jet aircraft. The TLAR are summarized in Table II. The use case has to cover a range of 3000 nautical miles with 130 passengers, at a cruise Mach number equal to 0.78 and an initial cruise altitude of 11000 meters. Take-off and landing field lengths are equal to 1900 and 1500 meters respectively.

Table II: Task A TLAR

Conventional Large Regional Jet Reference Aircraft (EIS: 2020)		
	Metric	**Imperial**
Range (102 kg /pax)	5556 km	3000 nm
Design payload	16329 kg	36000 lb
PAX	130 pax @ 102 kg	130 pax @ 225 lbs
MLW (% MTOW)	90%	
Cruise Mach (LRC)	0.78	0.78
Initial Cruise Altitude (ICA)	11000 m	36000 ft
TOFL (ISA, SL, MTOW)	1900 m	6233 ft
LFL (ISA, SL, MTOW)	1500 m	4921 ft
Engine	TURBOFAN high bypass	
Design objective	TO BE DEFINED by Teams	

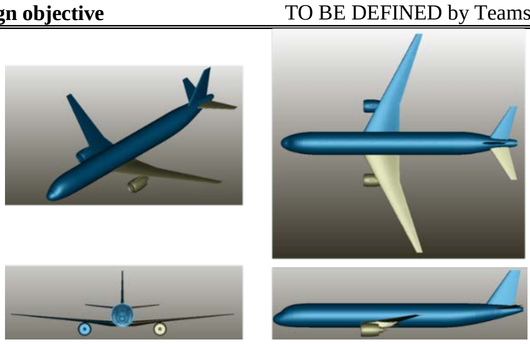

Figure 3 Three views of the CPACS file with the baseline aircraft.

The CPACS initialized use case has a wing area of about 113 m^2, a fuselage length of about 38 m and a main fuselage diameter of about 3.7 m. Nacelles and pylons have been "appended" to the wing geometry as external ".stp" files, in a specific CPACS branches. Main dimensions of the aircraft are summarized in Table III. The used engine is a high-bypass ratio turbofan and is provided as an engine performance deck by the AGILE consortium. It can be modified, substituted or used as rubber engine by the teams. All the dimensions and data are indicative and have to be changed during the AGILE Challenge.

Table III: AGILE Challenge use case main characteristics

Data are indicative and can be changed during the challenge.	
	Metric
Wing area	113 m^2
AR	~11
Fuselage length	~38 m
Fuselage diameter	~3.7m
Cabin abreast	5 (3+2)

5.2. TASK B

In AGILE, multiple technologies to enhance collaboration in MDO have been developed. Most of these technologies have been combined within one web-based environment: KE-chain. With KE-chain it is possible to setup and manage MDO problems following a five-step approach from definition of the design case to the optimization of the design solution (see Fig. 9). This five-step approach and the different applications and data standards developed in AGILE are more elaborately discussed in reference paper Van Gent et al.[9].

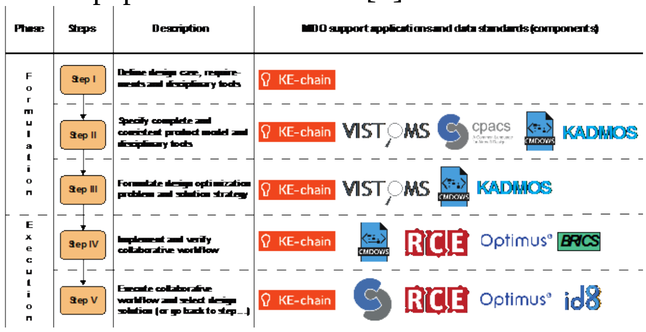

Fig. 9 KE-chain five-step approach

Within the scope of the AGILE Academy Challenge, the students were given the task to follow the approach based on their design task (see previous section) and the tools they were bringing into the project (e.g. an aerodynamic performance analysis code). Additionally, they were encouraged to independently organize their project by assigning different project roles. These roles, also called agents were introduced in the AGILE project and include:

- **Architect**: This agent is responsible for defining a suitable MDO architecture to meet the customer's requirements and therefore has to translate the customer's problem into a fully formalized computational architecture, containing the necessary design competences.
- **Integrator**: The integrator is responsible for converting the formalized neutral MDO system formulation provided by the architect, into an executable computational workflow by implementing it into a Process Integration and Design Optimization (PIDO) platform. Within the scope of the AGILE Challenge, the PIDO platform RCE, developed by the DLR, was used, as it is an open-source solution.
- **Competence specialist**: This agent is responsible for a specific design or analysis competence used within the scope of the MDO problem at hand. This can be for instance a design synthesis tool, a disciplinary analysis tool or an optimization service. Usually, multiple competence specialists are part of a single project.

Two other agents were defined in AGILE, namely the customer and collaborative engineer. In the AGILE Academy Challenge, the supervisors operate as both; customers to introduce and evaluate the tasks, and collaborative engineers to provide the students with the necessary tools and support to accomplish the tasks. For instance, during the initial phase of the Challenge, interactive support sessions on the AGILE framework were organized via webinars, in which the five-step approach was introduced and explained based on a realistic design case from the AGILE project.

The main goal of task B is for the students to implement and test different MDO architectures and problem solutions to solve a specific design task. To do so, it is important to first identify a set of parameters of interest for the MDO system (and later for the optimization), i.e. design variables, objectives and constraints. Secondly, the different tools used in the MDO system have to be connected via the KE-chain platform using the supporting systems associated with it. Finally, it is possible to apply different MDO system setups and problem solutions to solve the design task. Of course, the MDO architectures applied by the three teams can be very different, depending on the disciplinary design and analysis tools used and the focus of the design task. The teams can choose both freely, as already indicated in Table III.

5.3. TASK C

Task C is focused on the optimization through surrogate models. Surrogate models will be provided, and each team must perform its own optimization strategy in terms of objective function, variables and optimization algorithm. However, surrogate models can be also created by the team itself based on the workflows executed in task A.

5.4. RESULTS

Results coming from teams have been discussed and judged by AGILE consortium experts to establish the AGILE ACADEMY Challenge winner. Team 3 accomplished all the required tasks, resulting in winning team. For sake of brevity only team 3 results are here presented.

TASK A

The design task of team number 3 was the implementation of a solar power system on the AGILE provided baseline aircraft to supplement aircraft secondary power offtake and the analysis of the subsequent fuel burn. The preliminary step in building the workflow was to determine which tools will be used and what their interactions will be, making a catalogue of available competences, as shown in Fig. 10. Initial studies revealed several tool gaps in the Propulsion competency dealing mainly with the assessment of fuel savings due to reduced engine power offtake. None of the collaborators had any such assessment capability and therefore ISAE SUPAERRO and Concordia developed a tool to address this requirement. Furthermore, aircraft sizing tools such as VAMPzero and SUAVE recommended for use by the AGILE group were not suitable for the present design problem and therefore an in-house tool was developed by Concordia for this purpose. Direct operating cost calculations were incorporated into the sizing tool once the workflow was sufficiently well defined. It is important to note that other than the assessment of the groups available tools, parallel tool development activities were also carried out.

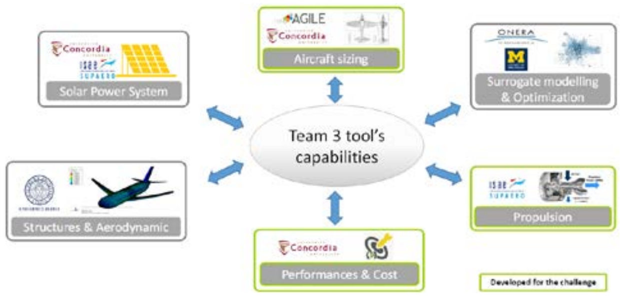

Fig. 10 Team 3 overview of existing, adapted and newly developed tools.

Fig. 11 shows the workflow developed to evaluate the effect of implementing SPS on the AGILE baseline aircraft. The tools involved in the process are listed and connected to show the various parameters that are exchanged. The input to the workflow is the aircraft baseline data which is fed into the SPS tool where the wing area is the driving parameter.

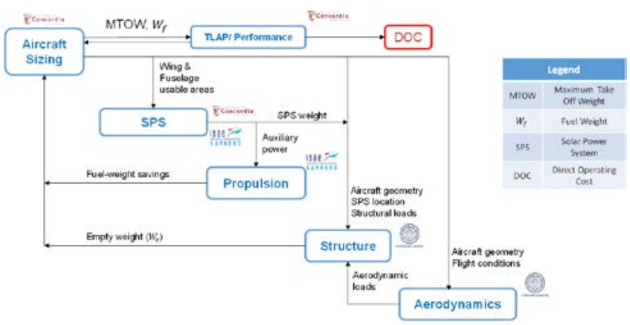

Fig. 11 Team 3 schematic workflow

The SPS tool determines the available power that can be generated using the specified wing area and passes it to the Propulsion tool. The Propulsion tool evaluates the amount of fuel that can be saved (in kg) by using SPS generated power to supplement systems power offtakes during ground and cruise segments. Aircraft parameters are also simultaneously passed to the structures and aerodynamics package hosted by the University of Pisa. Aerodynamic loads are derived for the aircraft configuration and then applied to the structure with an objective to size it for minimum empty weight. The empty weight and fuel savings are passed to the Aircraft Sizing tool that resizes the aircraft to maintain the same performance of the baseline.
The tool also determines the DOC of the aircraft for a year and prepares the data used for the next iteration. Workflow execution requires common exchangeable CPACS files to be read and written to by the individual tool owners, so tools compatibility have been ensured. These files are exchanged between owners after tool execution with an updated version number for each workflow iteration. The workflow consists of two modules, the first comprising of SPS and Propulsion and the second of Structures and Aerodynamics. The design problem was selected primarily based on tool availability but also because it required a truly multidisciplinary approach to investigate. Team competencies were also a driving factor in addition to the novelty of the idea considering recent trends in sustainable aviation. Tools used reflected competencies but were not formalized and directly applicable to this MDO problem. Additional tool capabilities were developed. AGILE KE-Chain platform was used to set up tool requirements and to record compliance.
Moreover, to speed-up execution of the workflow, the WAGNER tool developed by the University of Pisa was subjected to surrogate modelling activities using the Surrogate Modelling Toolbox (SMT). A model of the WAGNER tool was developed using SMT and was then integrated into the workflow.

TASK B

The KE-Chain platform was widely used from the outset of Task A. Documentation and requirements were specified on the platform and assigned to different team members to ensure compliance and all KE-Chain steps were performed. Using autonomously main features, such as KADMOS script and CMDOWS files, the relationships between variables and between tools have been established. This is visually

represented by a Repository Competence Graph (RCG). Combining the CPACS files and the tool definition, RCG helps map the different input and output variables coded in the CPACS files and how they interact between the different tools, where the top row blocks represent the input variables entering the tools and the left column blocks represent the output variable exiting the tools. A few more iterations are performed to produce a Fundamental Problem Graph (FPG), which streamlines and unclutters the data work flow by excluding, consolidating and addressing competence collisions (diagonal elements), and by selecting the key, desired design and state variable to be represented in the data work flow (off-diagonal elements).
The resulting team 3 converged MDAO workflow is shown in Fig. 12.

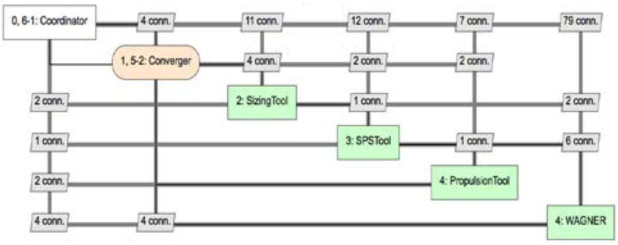

Fig. 12 Team 3 FPG KE-Chain workflow, converged MDAO

TASK C

Task C of the Agile Challenge required the creation and use of surrogate models of the workflow to perform optimization exercises. Surrogate models are required to help reduce the dependency on time and computationally intensive in house, specific tools. The surrogate model developed from data generated by workflow (TASK A) execution is then used for optimization. The aim of surrogate modeling is to create an analytical approximation of a model to reduce the cost and computational time. To train surrogate models, the user must provide some inputs and outputs, called training points or design of experiments (DOE) which are evaluated using the high-fidelity tools.
The surrogate modeling will be only used on the structure sizing tool Wagner because it is the only one with an important computational cost. The classical size of the DOE is ten times the number of variables. For each point of this DOE, a Wagner computation will be run, and each output will be stored. For each output, a dedicated surrogate model will be trained. Thus, the Wagner tool will be replaced by the surrogate. These approximations will ease the optimization phase of the entire workflow.
Optimization objective of team 3 was to minimize the total operational cost of aircraft based solar panels. The design variables of the optimization process are the solar panel efficiency, the wing area, the fuselage length, the fuselage diameter and the semi wingspan and tailspan. The following table provides the upper and lower bounds of the design variables.

Table IV: Upper and lower bounds of the design variables

Design variables	Lower Bounds	Upper Bounds	Units
Solar Panel Efficiency	0.25	0.55	-
Wing Area	100	250	m^2
Fuselage Length	32	40	m
Fuselage Diameter	3	4.5	m
Semi wing span	14	22	m
Semi tail span	5	8	m

Optimization is conducted with several constraints managed by SEGOMOE. The ratio between the fuselage length and the fuselage diameter and the aspect ratio of the wing are controlled within defined ranges. **Error! Reference source not found.** gives the ranges of these constraints. Other constraints are managed by each discipline within the specific tools: maximum admissible Von Mises stress and wing tip displacement for structural analysis and the usable areas for solar panels installation within the SPS tool.

Table V: Upper and lower bounds of the design variables

Constraints	Lower Bounds	Upper Bounds	Units
Fus length / Fus Diameter	8	10.5	-
Wing aspect ratio $\left(AR = \frac{Wing\ span^2}{Wing\ area}\right)$	6	15	-

The optimization of aircraft configuration will take 120 function evaluations.

FINAL RESULTS

The workflow was executed through the exchange and processing of CPACS files by each tool owner and the initial DoE generated by the SEGOMOE tool has been followed. [] shows the results of the sensitivity analysis conducted on the generated data. It helps compare the influence of each design variable on the direct operating cost. The most influent variable is the wing area as it affects the size of the solar panels. Consequently, it changes the available solar power used to reduce the fuel consumption, and therefore, the operating cost.

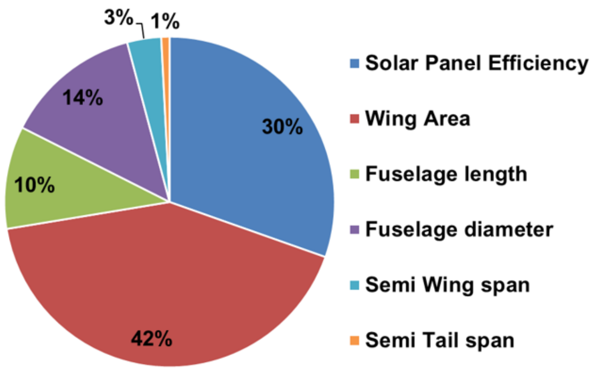

Fig. 13 Sensitivity analysis conducted on the direct operating cost

In addition to these preliminary results, the visualization features inherent within the Aerostructural analysis tools in the workflow allow a glimpse into the various aircraft configurations obtained from this study. These configurations were generated during the DOE phase and are used to build the surrogate model of the workflow. Subsequent optimization activities will then help determine the best configuration to minimize the direct operating cost of the aircraft.

Table VI introduces the design variables values for the maximum and minimum DOC aircraft configuration of the initial DoE and for the baseline aircraft (AGILE use case). Fig. 14 shows also the geometrical representation of these three configurations and gives the maximum take-off weight values (MTOW).

Table VI: Comparison of the design variables values for maximum and minimum DOC values of the initial DoE with the baseline

Design variables\Aircraft configuration	Baseline	Max DOC	Min DOC
Solar panel Efficiency $e_p\ (-)$	-	0.298	0.419
Wing Area $W_A\ (m^2)$	113	105 ↓	244 ↑
Fuselage Length $L_f\ (m)$	38	32 ↓	33 ↓
Fuselage Diameter $D_f\ (m)$	3.7	3.5 ↓	4.5 ↑
Semi wing span $S_{wing}\ (m)$	17.5	16.8 ↓	16.3 ↑
Semi tail span $S_{tail}\ (m)$	6.5	6 ↓	5.7 ↓

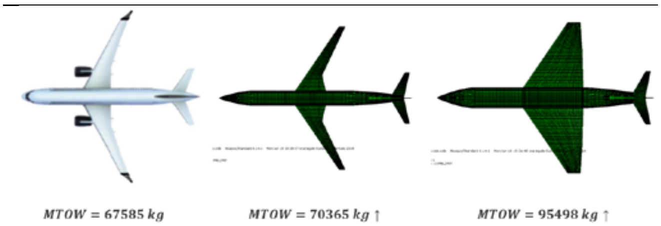

Fig. 14 Sensitivity analysis conducted on the direct operating cost

MDAO

Optimization activities were initiated to target the established objectives of a minimization of Direct Operating Costs, subject to various global and tool level constraints. The nature of the constraints and the inherent multidisciplinary aspect of the design problem makes it difficult to apply classic global optimization methods to. Evolutionary algorithms require a restrictively large number of tool executions whereas gradient based approaches may not be compatible with all the different tools. To mitigate all these problems, a Mixture of Experts approach is used in conjunction with surrogate modelling techniques through the SEGOMOE tool developed by ONERA. The optimization process considers 6 design variables subject to four constraints (up to two internal tool constraints). The aircraft geometrical constraints like the fuselage length to diameter and aspect ratios were derived by considering the bounds prevalent in existing aircraft of the same class.

Internal tool constraints were limited to the aero-structural analysis tool and mainly involved maximum Von-Mises stresses and limits on wing tip displacement.

An initial DOE dataset of 24 points is required to initialize the surrogate model and a further 96 were required for optimization, bringing it to a total of 120 evaluations of the complete workflow. The workflow was evaluated for the initial 24 DOE configurations and subsequent optimization iterations are currently underway. A preliminary sensitivity study on the DOE data showed that wing area, panel efficiency and fuselage diameter were among the main contributors to the direct operating cost. Optimization runs of the workflow so far have showed a trend towards lower panel efficiencies, wing areas and higher fuselage diameters resulting in the lowest direct operating cost. A promising trend is seen as some of these configurations almost match the direct operating cost of the baseline aircraft. Optimization results is shown in Fig. 15.

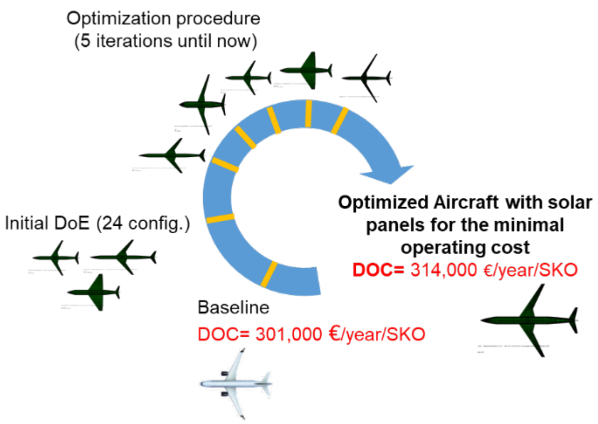

Fig. 15 Optimization Results

Acknowledgements

The research presented in this paper has been performed in the framework of the AGILE project (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) and has received funding from the European Union Horizon 2020 Programme (H2020-MG-2014-2015) under grant agreement n◦ 636202. The authors are grateful to the partners of the AGILE consortium for their contribution and feedback.

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Contact Author Email Address

Corresponding author:
Pierluigi Della Vecchia;
pierluigi.dellavecchia@unina.it or

Prajwal Shiva Prakasha;
mailto:prajwal.prakasha@dlr.de

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