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MDO APPLICATIONS TO CONVENTIONAL AND NOVEL TURBOPROP AIRCRAFT WITHIN AGILE EUROPEAN PROJECT

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Abstract

In this paper, multidisciplinary design optimization within the AGILE European project is applied to two turboprop aircraft. The first one is a conventional configuration characterized by wing mounted engines, while the second one is an innovative configuration with rear engines installation on the horizontal tail tip with an innovative power plant architecture. Both configurations are suited for 90 passengers, a design range of 1200 nautical miles and a cruise Mach number equal to 0.56.

The methodologies used to analyze both configurations include aerodynamic performance in clean, landing and takeoff configurations, mission performance, weight and balance, stability and control, emissions, in terms of Global Warming Potential parameter, and Direct Operating Cost estimation. The latest two will be considered as objective functions for the optimization loop.

Aim of this paper is to compare both configurations highlighting benefits and limits. Particular attention has been posed on the innovative approach used to analyze the use cases. The whole design process is made up of different tools belonging to a specific partner. Each partner is specialized in a specific discipline. The design process has been setup to be completely automated so that, partners, distributed worldwide are able to communicate and exchange results through remote connection. In this way each discipline has been assigned to the suited specialist.

1 Introduction

The present paper deals with the Multidisciplinary Design Analysis and Optimization (MDAO) applied to two turboprop aircraft configurations within AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) European project [1].

AGILE is a three years project coordinated by the DLR and funded by European Union (EU) through the HORIZON2020 program and it aims to create an evolution of MDO, promoting a novel approach based on collaborative remote design and knowledge dissemination among various teams of experts. The aim of the project [2][3] is to develop advanced MDO and efficient multisite collaboration techniques to reduce convergence time and to face the lack of knowledge on how to setup optimization workflows involving lot of disciplines.

The paper presents the analyses comparison of a conventional and an innovative turboprop configuration analyzed during the third Design Campaign (DC) of the project within the Work Package 4 (WP4), in which the task 6 (T4.6) has been leaded by University of Naples Federico II (UniNa) as both specialist and integrator [4]. In this WP, six different disruptive aircraft configurations have been analyzed starting from specific Top Level Aircraft Requirements (TLARs). In T4.6, TLARs have been assigned by LEONARDO company which is the task architect. Turboprop use cases have been assigned to UniNa team because in the last three decades it gained and improved its experience in design and optimization of turboprop aircraft [5][6][7]. Moreover, many experience has been carried out on numerical and experimental design and analysis [8][9][10][11] and on the development of design methodologies through numerical and experimental investigations [12][13] with applications on light and general aviation aircraft [14][15][16].

The T4.6 activities have been carried out to verify and test the applicability of the AGILE MDO technologies, developed during the whole project duration, to unconventional aircraft configurations taking advantage of a strong and well-defined collaborative and remote design approach [4].

In the following sections aircraft configurations characteristics and TLARs are summarized (Sec. 2), then, the design approach is described (Sec. 3) followed by aircraft analyses results comparison (Sec. 4) and, finally, conclusions are addressed (Sec. 5).

2 Aircraft initialization

Both turboprop configurations, wing mounted engine (WM) and rear mounted engine (RM), have been preliminary sized by according to the TLARs given by Leonardo company summarized in Table I. Leonardo also requested to comply several aerodynamic requirements listed in Table II and Table III.

The preliminary aircraft initialization leaded to aircraft characterized by the same wing planform and fuselage but a different horizontal and vertical tail planes due to wing position, along the longitudinal axis, and engine position. In Table IV main planform parameters are summarized to fix a reference aircraft to be compared with the optimized ones.

Table I: Regional turboprop aircraft configurations TLARs provided by Leonardo company.

	Metric	Imperial
Design Range	2222.4 km	≥1200 nm
Design payload	9540 kg	21032 lbs
Max. payload	11590 kg	25552 lbs
PAX	90 pax @ 106 kg	90 pax @ 233.7 lbs
MLW (% MTOW)	97% MTOW	
Cruise Mach (LRC)	0.56 @ 7620 m	0.56 @ 25000 ft
Maximum Operating Altitude	7620 m	25000 ft
Climb Time (1500 ft to 200 FL)	13 min	
TOFL (ISA, SL, MTOW)	≤1500 m	4920 ft
Landing distance	≤1500 m	4920 ft
Max. operation speed (Vmo / Mmo)	270kcas/Mach 0,60	
Dive Mach number (Md)	0,64 Mach	
Fuselage diameter	3.53 m – 5 abreast	139.17 in - 5 abreast
Service life	≥110000 CY	
Fuel reserves	5% B.F - 100 nm Alternate	
Holding	30 min @ 457 m	30 min @ 1500 ft
A/C configuration	High-wing (wing-mounted engines), Low wing (rear mounted engines)	
nEngine	2 - TurboProp	
Design objective	Minimum D.O.C.	
External Noise	CHAP14 – 15 epndb	

Subsequently, all aircraft characteristics in terms of mass breakdown, wings and fuselage have been stored in a common file format characteristic, high lift devices, mission and so on have been written in a common file format, based on XML technology, called CPACS (Common Parametric Aircraft Configuration Schema) [17][18]. Then, the files have been used by the partners as an Overall Aircraft Design exchange database in which the specialists can add results of their calculations that can be used by others as input for their tools.

Table II: Aerodynamic TLARs for WM configuration.

WM Reference Aircraft		
Condition	C_L	Efficiency
CLIMB	0.75	16
CRUISE	0.51	16.5
OEI	1.30	14.5
		C_{Lmax}
TAKE OFF & APPROACH		2.3
CLEAN		1.7
LANDING		3.0

Table III: Aerodynamic TLARs for RM configuration.

RM Reference Aircraft		
Condition	C_L	Efficiency
CLIMB	0.8	16.5
CRUISE	0.55	17.5
OEI	1.16	14
		C_{Lmax}
TAKE OFF & APPROACH		2.3
CLEAN		1.7
LANDING		3.0

Table IV: Aircraft main geometrical characteristics, WM and RM configurations.

WM and RM Reference Aircraft		
Wing	**WM**	**RM**
AspectRatio (AR)	12	12
Area (S_w)	78 m^2	78 m^2
Span(b_w)	30.6 m	30.6 m
Root chord (c_r)	3.33 m	3.33 m
Kink chord (c_k)	3.22 m	3.22 m
Tip chord (c_t)	1.16 m	1.16 m
Mean aerodynamic chord (mac)	2.74 m	2.74 m
Fuselage		
Overall length (L_f)	29.29 m	29.29 m
Diameter (d_f)	3.53 m	3.53 m
Vertical Tail		
Area (S_v)	18 m^2	23.53 m^2
Span (b_v)	5.38 m	5.27 m
Horizontal Tail		
Area (S_h)	14.72 m^2	32.8 m^2
Span (b_h)	8.18 m	9.06 m

Starting from the geometric characteristics has been possible to make a preliminary mass breakdown estimation provided by Leonardo company, summarized in Table V, where the Maximum TakeOff Weight (MTOW), Zero Fuel Weight (MZF), Operating Empty Weight (MOEW), Landing Weight (MLW), payload mass ($M_{payload}$) and fuel mass (M_F) are listed.

Finally, in Fig. 1 and Fig. 2WM and RM configurations are respectively shown using TiGL Viewer software [19] developed by DLR.

Table V: Preliminary mass breakdown for WM and RM configurations by Leonardo company.

WM and RM Reference Aircraft		
Weights	**WM**	**RM**
MTOW	35380 kg	37500 kg
MZFW	33020 kg	35060 kg
MOEW	21430 kg	23470 kg
Mpayload	11590 kg	11590 kg
MLW	34319 kg	36375 kg
M_F*	2360 kg	2440 kg

*Related to design payload condition and based on SFC = 0.36 lb/hph

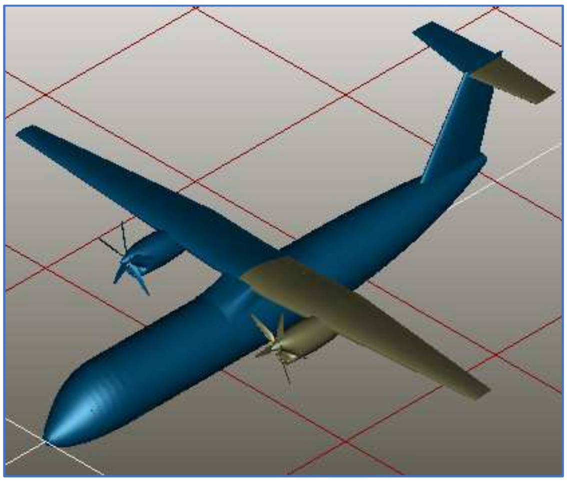

Fig. 1. WM configuration in TiGL Viewer**.**

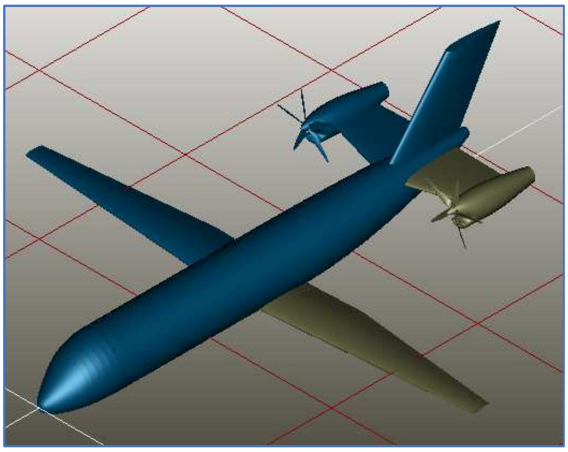

Fig. 2. RM configuration in TiGL Viewer.

3 MDAO approach

The first step concerns the set-up of MDA workflows, one for each configuration, involving several and specific partners that can contribute to improve the accuracy of analyses in a specific discipline thanks to their expertise. At this stage, the architect and the integrator identify, among the project partners, tools and specialists to be involved in building-up the analyses workflow, suited to turboprop aircraft. Each partner, as a specialist in a specific discipline, provides his own competence(s) (low/medium level of fidelity L0-L1) through the release of computer codes and methods regarding fields such as aerodynamics, aircraft weights estimation, mission analysis, costs and so on. Each one of these CPACS-compliant competences is stored in a tool, a black box [20], which can be run in a remote manner and the results, stored in the CPACS file, can be used by other partners as input for their calculations (if needed). Thanks to this approach a Multidisciplinary Design Analyses (MDA) workflow has been set allowing to analyze an arbitrary number of CPACS files (aircraft configurations) and to exchange the results among the partners. The workflow integration is automatically generated using Ke-Chain, Kadmos and Vistoms packages created during the second year of the project [20].

The abovementioned software packages allow to set-up the whole analysis chain starting from the TLARs. Several MDA architectures analysis can be defined by managing partners' input and output CPACS files. Once a specific architecture analysis has been set up it is possible to export an automated executable workflow that, can be run, in a remote way using RCE software [22] and Brics package [23]. Furthermore, is also possible to check how many data connections exist between tools and if those connections are the expected ones, manually customize the workflow and make it faster and more efficient. In Fig. 3 the MDA workflows in Ke-chain environment is shown, while in Fig. 4 the same workflow in executable format in RCE environment is shown.

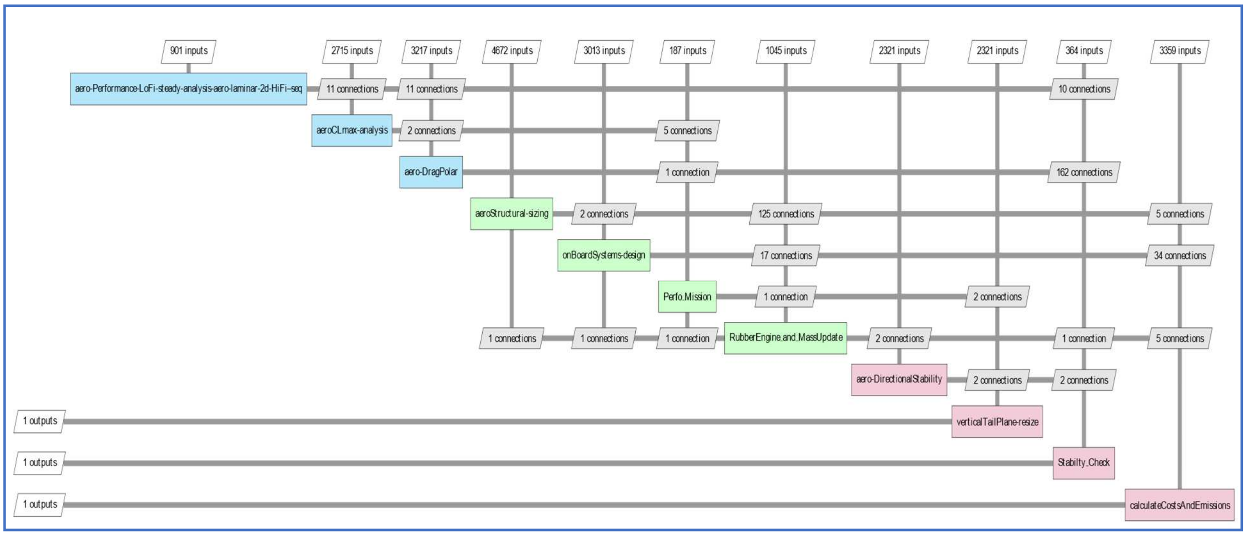

Fig. 3. MDA workflow in Ke-chain environment. Visualization through Vistoms package

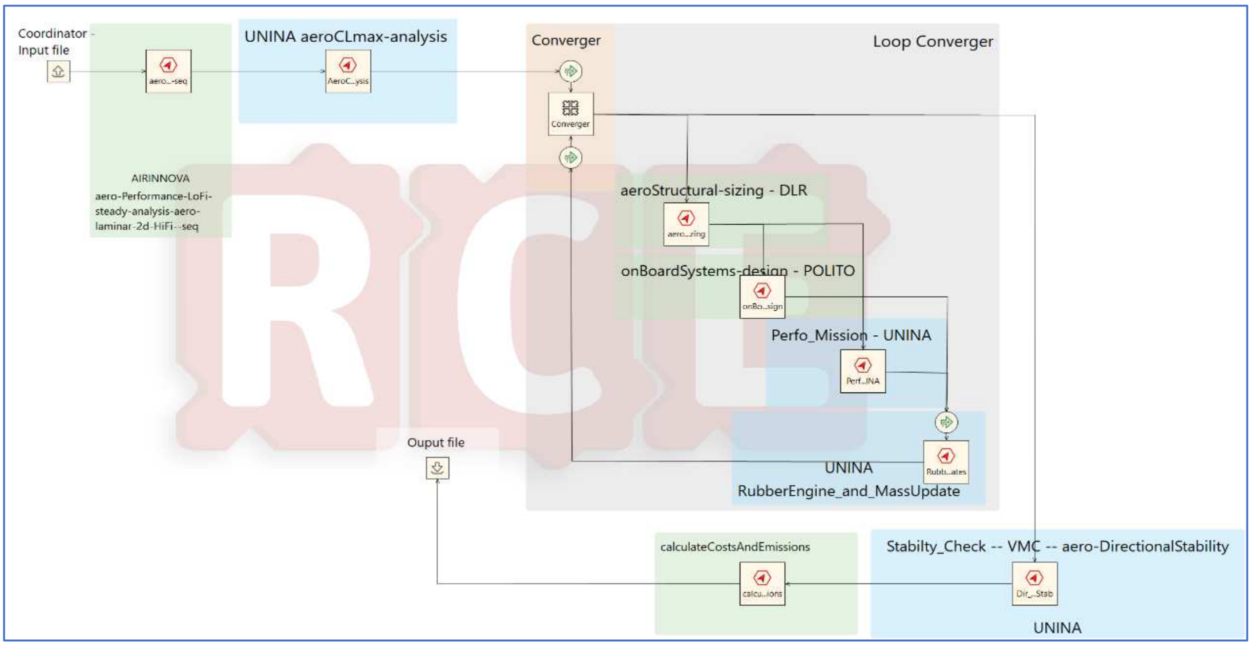

Fig. 4. Executable MDA workflow in RCE environment

This approach allows to reduce time and cost in the preliminary and conceptual design phase because of the easy connection among partners that can share and exchange calculations and results using the CPACS file. This technology allows to reduce the total amount of interconnections among partners from $n(n-1)$ to $2n$, where n is the number of involved partners, as shown in Fig. 5, and the available software speed up the entire set up phase.

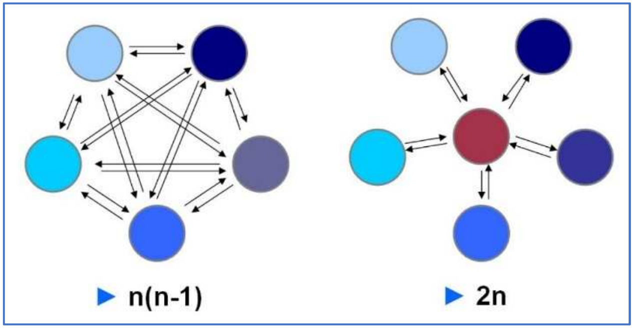

Fig. 5. Reduced number of interconnections among partners thanks to CPACS technology

Following the same procedure, has been also possible to compute a Design of Experiments (DOE) campaign, see Fig. 6, lunching the MDA chain 80 times changing 4 different wing main parameters [4]. In this way, several surrogate models such as aerodynamics, structures, on board systems, mission performance, engine and costs have been created. The aim of the previous steps is the creation of a database in which are stored results related to many different aircraft configurations, in terms of main wing parameters such as span, area, taper ratio. This approach allows to build a cluster for each discipline and use surrogate models in the MDO workflow.

In the last step, the Multidisciplinary Design Optimization chain has been assembled making use of the surrogate models created in the previous step. The main advantage is that the surrogate models can be used as one of the tools in the chain, so they can be in house developed or provided by a specific partner and used in remote manner. Moreover, it is possible to apply the Response Surface Methodology (RSM) [25][26]to these databases so that, fixed the input variables, the results can be obtained with a simple interpolation, speeding up all the process. The accuracy of the RS can be improved by performing some high-fidelity analyses of specific configurations.

The described approach can lead to optimized results characterized by a quietly high level of fidelity (from L0 to L3) in a time period quietly short considering that each partner focuses on his own discipline and then results are collected, assembled in *black boxes* and used in automated manner. The optimization task can be performed choosing among several optimization algorithms and several workflow architectures.

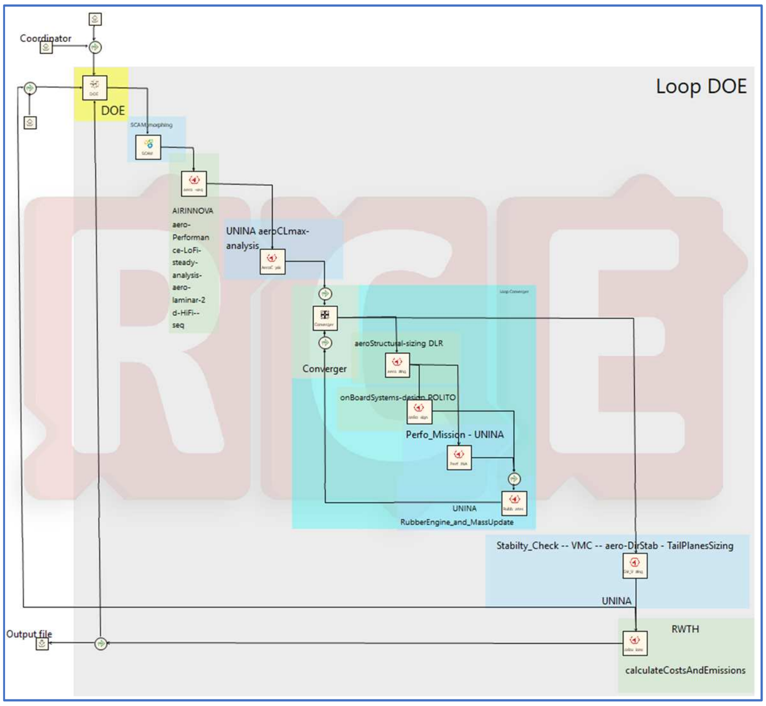

Fig. 6. DOE workflow in RCE environment

4 WM and RM use cases. Results and comparison

The optimization problem is defined as follow (see Table VI): the objective function for both the configurations is the DOC. Together with this, to target CleanSky2 objectives, the architect added a second objective defined as the total global warming potential (GWP), defined accordingly Ruijgrok and Van Paassen [27]. Moreover, the optimization problem constraints, coming from the TLARs shown in Table I and aircraft static stability margin (SSM), imposed by the integrator, have been fixed. The variables for this application are the main wing planform parameters, where λ_w is the taper ratio and X_{LEw} is the wing leading edge position along the x axis, summarized in Table VI.

Table VI: Optimization problem, variables and constraints

Objective functions	Min: $f_1 = DOC$ $f_2 = GWP$
Constraints	$SSM \geq 0.05\ (5\%mac)$ $TOFL \leq 1500\ m$ $LNFL \leq 1500\ m$
Variables	$XLEw$ ARw λ_w b_w

The WM configuration is characterized by high wing with under wing engine installation and T-tail, while the RM has a low wing and rear engine installation on horizontal tail tip. For each layout, a suited engine deck has been provided by CIAM as engine specialist [28].

To face stability problems, due to a high value of maximum rearward position of center of gravity, the wing is back shifted along x axis with respect to WM configuration. The low wing configuration has been used to avoid the interference between wing wake and horizontal tail. In Fig. 7 the comparison between potato diagrams of the two configurations is shown.

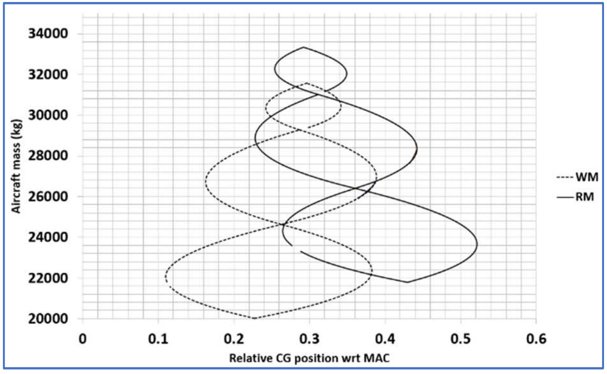

Fig. 7. WM and RM baseline. Potato diagrams comparison

Due to different engine installation, the CG shift of WM configuration is in the range 11% - 39%, while for RM is 22.8% - 59%. The latter configuration can lead to a very large CG excursion which can also affect aircraft performance. A wide CG excursion could imply a very big horizontal tail to trim the aircraft in the most rearward CG positions resulting in a reduction of the maximum lift capabilities; while in the most forward CG position the longitudinal static margin could be very high implying a very large download on the tail to trim the aircraft. This latter will reduce the cruise efficiency affecting the fuel burned and aircraft DOC. One possible solution could be a reasonable reduction of the CG excursion.

Although some disadvantages due to rear engine installation, this choice can lead to reach several advantages such as cabin noise reduction, community noise reduction because of the absence of T-tail avoiding the noise reflection, more efficient high-lift system with a possible increase in aircraft maximum lift coefficient and using laminar airfoil for the main wing to reduce the total friction drag. In Fig. 8 drag polar charts comparison is shown.

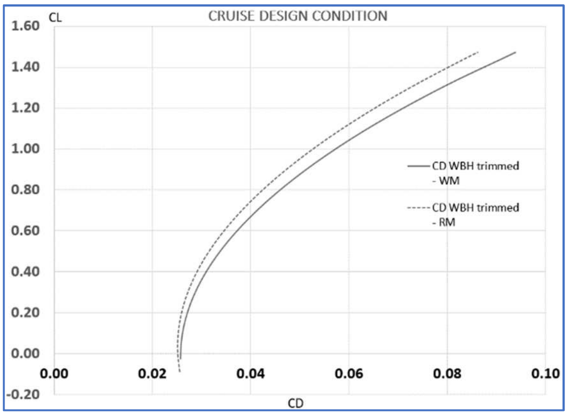

Fig. 8. Drag polar diagrams for trimmed configuration. comparison between WM and RM baseline

In cruise condition the friction drag for WM configuration is equal to 262 drag counts while for the RM is reduced by 20 drag counts thanks to the laminarity of the main wing.

The SSM of the RM and WM configuration are equal to 2% and 5% of MAC respectively. Starting from these configurations, the optimization task has been performed meeting the constraints described in Table VI and aiming to obtain aircraft with SSM not lower than 5%.

The optimization algorithms OMOPSO and ε-NSGAII [4] converged on similar results both in terms of design variables and objective functions reaching different geometrical solutions for RM and WM, as shown in Fig. 9 and Fig. 10 to minimize DOC and emissions, as listed in Table VII, Table VIII, Table IX and Table X.

Table VII: Optimized and reference WM configurations geometry comparison

	WM Reference	**WM Optimized**
AR_w	12	14.79
S_w	78 m2	78.17 m2
b_w	30.6 m	34 m
c_r	3.33 m	3.01 m
c_k	3.22 m	2.91 m
c_t	1.16 m	1.05 m
mac	2.74 m	2.49 m
X_{LE}	12.80 m	12.84 m
Horizontal Tail		
S_h	14.72 m2	13.39 m2
b_h	8.18 m	7.81 m
Masses		
Block Fuel	3920 kg	3798 kg
MTOW	35496 kg	35851 kg

Table VIII: Optimized and reference RM configurations geometry comparison

	RM Reference	RM Optimized
AR_w	12	14.87
S_w	78 m^2	77.74 m^2
b_w	30.6 m	34 m
c_r	3.33 m	3.00 m
c_k	3.22 m	2.90 m
c_t	1.16 m	1.04 m
mac	2.74 m	2.47 m
X_{LE}	13.8 m	13.98 m
Horizontal Tail		
S_h	32.8 m^2	29.79 m^2
b_h	9.06 m	8.63 m
Masses		
Block Fuel	3981 kg	3915 kg
MTOW	37317 kg	37671 kg

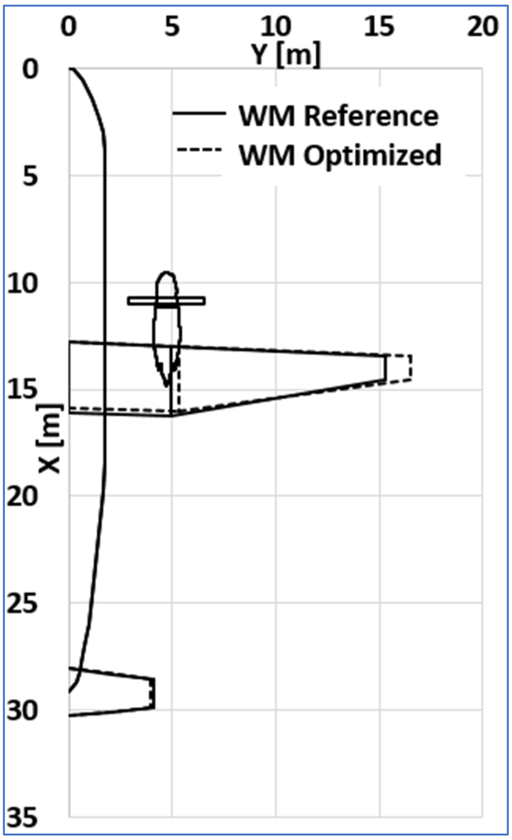

Fig. 9. WM reference and optimized layout comparison

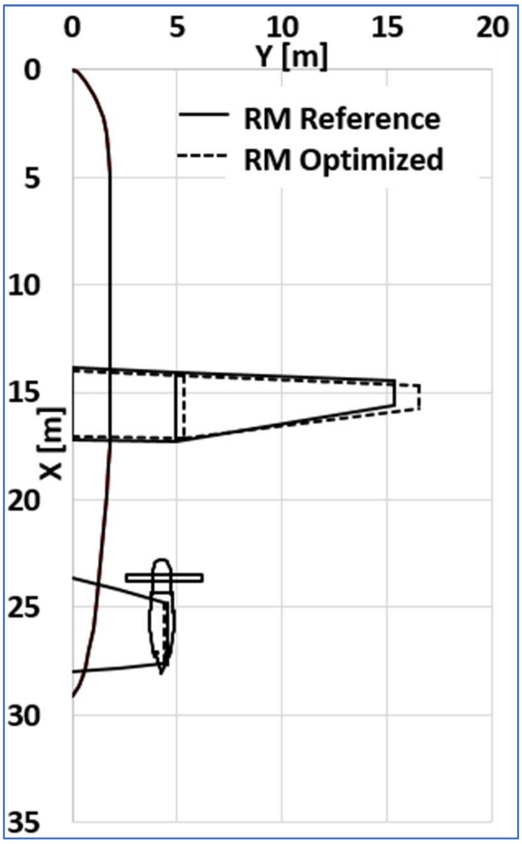

Fig. 10. RM reference and optimized layout comparison

Table IX: Objective functions comparison for WM configuration

WM layout			
	Baseline	Optimized	%
DOC ($/flight)	17205.76	16829	2.1
DOC (Millions $/year)	36.95	36.14	
GWP (kg/flight)	13191.58	12780.76	3.1
GWP (tons/year)	28335.52	27453.08	

Table X: Objective functions comparison for RM configuration

RM layout			
	Baseline	Optimized	%
DOC ($/flight)	16974.34	16750.62	1.3
DOC (Millions $/year)	36.46	35.98	
GWP (kg/flight)	13396.86	13198.42	1.5
GWP (tons/year)	28776.45	28350.21	

Considering that, for this specific aircraft category, the possible number of flights per day is equal to 6 and it works 358 days per year, assuming 7 days for maintenance check A and B, it is possible to save more than 800 k$ per year for WM and more than 450k$ for RM in terms of DOC. Furthermore, it is possible to consider that the GWP reduction means a decrease of more than 850 tons for WM and more than 400 tons per year for RM in terms of emitted CO_2 mass.

5 Conclusions

The AGILE methodology has been validated and applied to two different turboprop layouts showing the powerful of this kind of approach. The collaboration and support provided by each partner together with strong process automation has allowed to speed up the setup of the entire design process reducing time by 40% with respect to setup the workflow and data exchanging manually. Furthermore, heterogeneous team of experts has ensured a good level of affordability and accuracy of the results obtained.

Applying this paradigm and technologies, a conventional and an innovative turboprop aircraft have been analyzed and optimized. Starting from the same TLARs, both the baseline configurations have been used to perform a DOE to obtain surrogate model for each discipline. The surrogates are based on 80 different configurations for each aircraft layout obtained changing 4 main wing planform parameters. Then optimization algorithms have been applied achieving WM and RM optimized configurations which allow to reduce, in one year, the emitted CO2 mass by about 3.1% and 1.5% and DOC by 2.1% and 1.3% respectively.

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