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AIRCRAFT CONCEPTUAL DESIGN IN A MULTI-LEVEL, MULTI-FIDELITY, MULTI-DISCIPLINARY OPTIMIZATION PROCESS

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Abstract

As the main French actor in aeronautics applied research, Onera faces the challenge to master complexity and generate innovative responses to industry, agencies and MoD needs. In particular, its multidisciplinary skills in aerodynamics, propulsion, structure, sensors, guidance and control and performance analysis are used to perform vehicle system integration and optimisation, either to integrate new technologies or define prospective views of operational vehicles. To support this capability, Onera has for the last decade initiated an important methodological effort to improve the efficiency of vehicle design processes, developing tools and techniques in the field of MDO.

Within the project ARTEMIS (Advanced R&T Enablers for Multidisciplinary Integrated Systems) carried out in collaboration with Airbus, Onera developed a multi-level, multi-fidelity and multidisciplinary design and optimisation of a civil transport aircraft. The aim of this paper is to illustrate the progress made on setting up a robust and efficient conceptual design process, integrating more accurate data coming from a high fidelity optimisation.

After a presentation of the tool enabling a conceptual design level optimisation of the aircraft, the paper details the coupling between this two processes based on different fidelity level tools. Subsequently, the authors explain the demonstrators set-up in ARTEMIS and specify the use case. The core of the publication is then dedicated to explaining the different approaches that have been explore in order to manage the exchanges between a rapid low-fidelity process and a high fidelity one. This section is completed with the presentation of some optimisation results that emphasize the interesting combination of both processes. In this part, authors have the opportunity to illustrate the effect of the penalty term, a component introduced in the objectives functions to have a consistent search in the design space for both processes.

1 Introduction

Next generations of civil transport aircraft will have to meet more and more stringent requirements in terms of performance, environmental impact and safety levels. In order to meet these goals, design engineers will both develop innovative solutions optimizing interactions between various disciplines and explore radically different aircraft configurations. In addition, given the strong industrial competition in aeronautics, development phases from conceptual to detail design of a new aircraft must be reduced with the objective of advancing its date of entry into service and thus capturing market shares.

In ARTEMIS (Advanced R&T Enablers for Multidisciplinary Integrated Systems), a project in collaboration with Airbus, Onera proposes then to develop a demonstrator of a Multi-level, Multi-fidelity, Multi-Disciplinary Optimization process enabling a faster, larger and more reliable exploration of the design space. The idea is to couple a Bi-Disciplinary Process

(PBD) based on high fidelity tools carrying out the aero/structure optimization and a Global Aircraft Process (GAP) that optimizes the overall aircraft from a system point of view using low fidelity models. Given its analysis tools, PBD can provide reliable data in an efficient manner while GAP enables to consider the impact of more disciplines and to rapidly assess different areas of the design space. As a first step in the development of this demonstrator, the coherent multi-level, multi-fidelity process is tuned on a classical tubes and wing configuration.

The objective of this paper is to detail the role of the aircraft conceptual design process (GAP according to the ARTEMIS nomenclature) and its exchanges of information with a high-fidelity bi-disciplinary process introduced in [1] in order to achieve a multi-level, multi-fidelity optimisation.

In the first chapters, the authors of this paper, presents the Global Aircraft Process and the multi-level coupling between GAP and PBD. To complete this introductory part, the third section details the demonstrator's set-up as well as the reference use-case within ARTEMIS. The following sections focus on the development of the multi-level, multi-fidelity coupling and the outcomes of the demonstrators.

2 Conceptual Design optimisation: the Global Aircraft Process

The Global Aircraft Process aims at sizing the aircraft according to a reference mission profile and the associated optimization of the wing planform, meeting a certain number of constraints regarding performances. The process is based on a tool identified as ACODE (Airliner COnceptual DEsign), enabling both the assessment and optimisation of a complete vehicle at the conceptual level considering several disciplines. The main modules considered within this multidisciplinary process are Aerodynamics, Propulsion, Weight assessment and Mission performances. The organisation of the Multi-Disciplinary Analysis (MDA) within ACODE is illustrated in Figure 1.

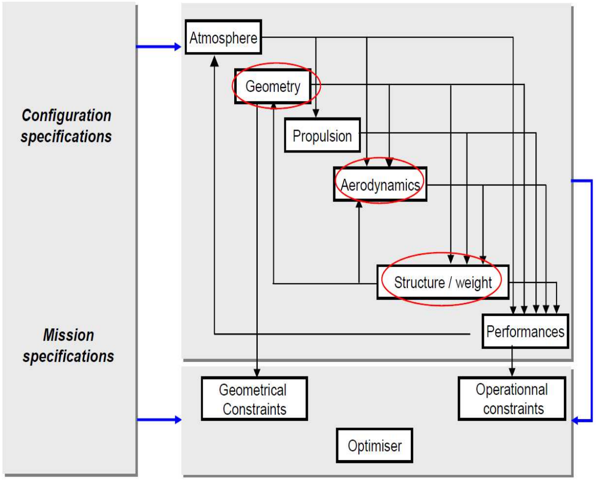


Figure 1 : Breakdown of the ACODE modules

Within ARTEMIS, the retained design variables, at GAP level, are related to the wing planform:

- the wing span: B
- the leading edge sweep angle: Φ
- the external taper ratio: e

During the optimisation, constraints taken into account are:

- Approach speed
- Balanced field Length (BFL)
- Available wing volume for fuel

The GAP objective function is defined as

$$F = 0.5 \times MTOW + 0.5 \times M_{fuel}$$

where

- MTOW is the Maximum Take Off Weight
- M_{fuel} corresponds to the fuel weight (including reserves).

In the case of a multi-objectives optimisation, the existing MDA is coupled with a genetic algorithm optimizer and a set of best designs is calculated. In the following figure, the obtained Pareto front for a multi objectives optimisation aiming at the minimisation of both the Maximum Take Off Weight and the fuel weight can be observed.

3 Multi level coupling

Instead of developing a more complex process capable to handle both low fidelity and high fidelity optimisations, ARTEMIS aims at achieving the multi-level, multi-fidelity capability by coupling two distinct processes. The idea is to clearly combine the assets of both GAP and BDP while minimizing their drawbacks.

As illustrated in Figure 1, a first link shows outcomes of BDP used by GAP. Since BDP carries out a strongly coupled High Fidelity Aero / Structure optimization based on CFD and CSM models, it provides reliable data. The objective is to transfer some of the knowledge about aerodynamics and structure acquired during BDP iterations. Drag data and weight of wing primary structure are then extracted and transferred to GAP to make more accurate estimations.

The second link underlines the information provided by GAP and given to BDP. Since GAP is making an optimisation from an Overall Aircraft Design point of view on Mfuel and MTOW, high level constraints are integrated in the analysis. The objective is to transfer some of this knowledge about the overall system under the form of an aero / structure tradeoff coefficient α is extracted. This coefficient is then orienting the PBD optimization since it is used in the objective function.

In order to complete the iterative loops between BDP and GAP that share the same global design variables, penalty terms are added to the objectives functions to make sure that the independent optimization completed by a process is not moving away from a design space defined by the other process.

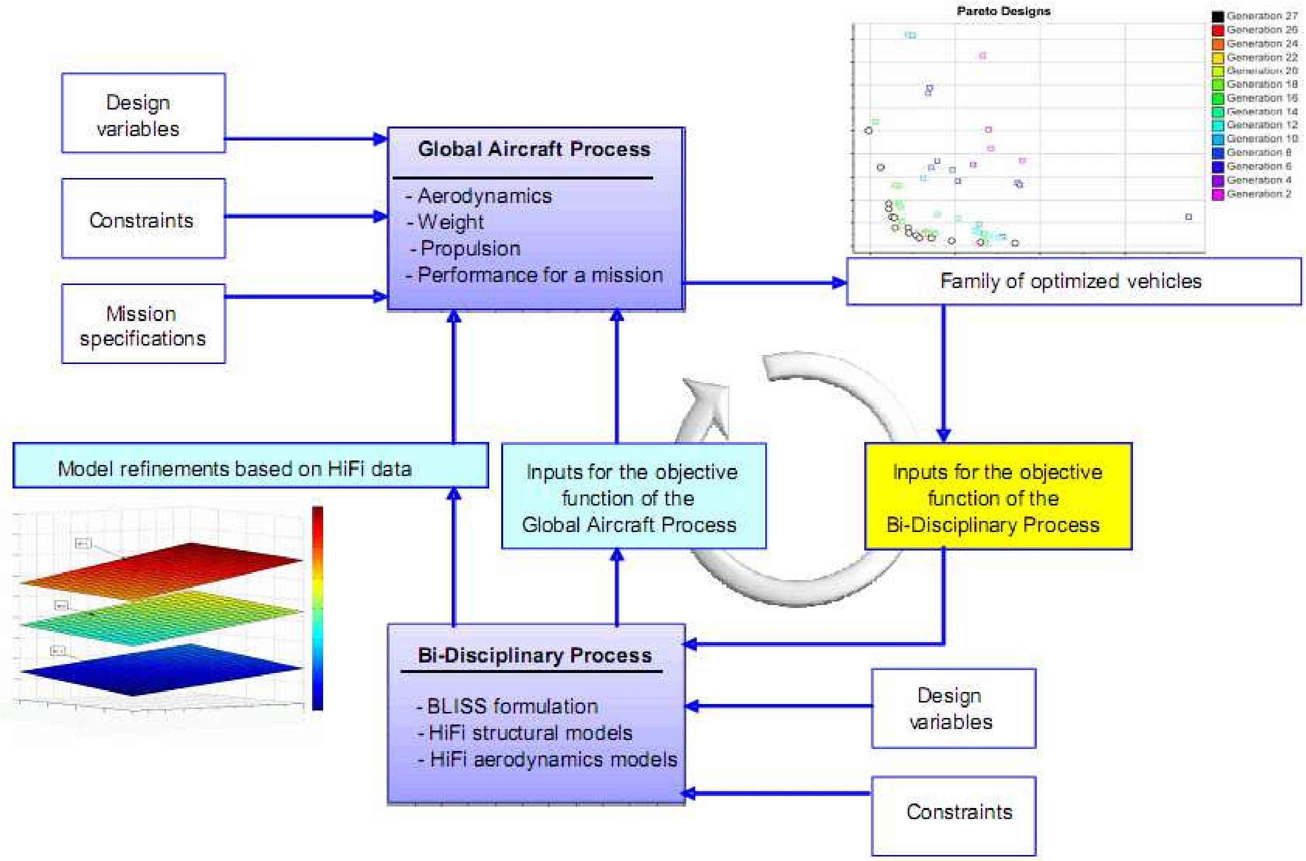


Figure 2 : Multi-level coupling in ARTEMIS

4. Demonstrator set-up in ARTEMIS

4.1 Versions of the ARTEMIS demonstrator

During the project, 2 demonstrators have been developed in order to increase the number of exchanges between GAP and BDP variables.

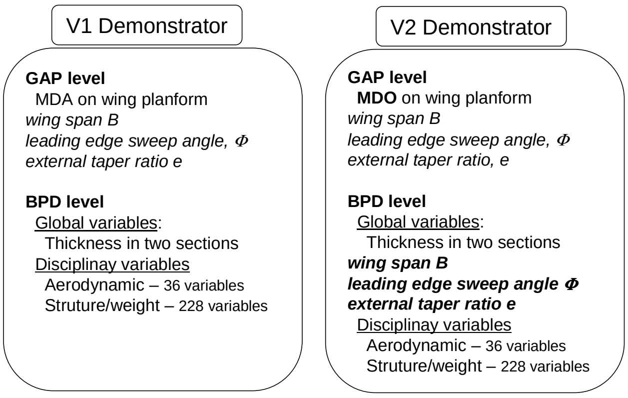


Figure 8: Overview of Demonstrators

In the V1 demonstrator, the planform remains unchanged and GAP only performs a MDA of the aircraft every time the BDP has converged to a best wing design (in terms of thickness) and has provided a new set of drag data and weight of wing primary structure.

In this version, the BPD objective function is defined as:

$$F(X,Z) = (1-\alpha)W_{wing} + \alpha C_D$$

where

- Wwing is the Structural mass of the wing
- C_D the total drag for cruise configuration
- α the trade off coefficient provided by the GAP

In the second version of the demonstrator (V2), GAP and PBD share the wing planform data (3 variables) and an optimisation is run at the GAP level. Then, for the Bi-Disciplinary Process, the objective function is modified to avoid searches in a design space that is not compatible with the results of GAP. The objective function becomes then:

$$F(X,Z) = (1-\alpha)W_{wing} + \alpha C_D + P$$

where P is the penalty term defined as:

$$P = rp.[(e_{GAP} - e)^2 + (B_{GAP} - B)^2 + (\Phi_{GAP} - \Phi)^2]$$

where

- rp is a penalty coefficient iteratively adjusted during exchanges between GAP and BDP
- e_{GAP} is the optimized value of e provided by GAP
- B_{GAP} is the optimized value of B provided by GAP
- Φ_{GAP} is the optimized value of Φ provided by GAP

One has to note that the optimisation performed with GAP is influenced by a similar penalty function to be sure that the search for an optimum solution is taking into account information provided by the Bi-Disciplinary Process

4.2 ARTEMIS test case

In ARTEMIS, the retained test case is the aero-elastic optimization of the wing for a long rang aircraft. This application presents at least two main advantages for the demonstration of the coupling process:

- At the BDP level, giving the increasing part of composite components in the primary structure, flexibility plays a major role in aircraft performance and the best compromise has to consider opposing objectives.
- At the GAP level, this type of aircraft will spend more than 90 % in cruise configuration were the aerodynamics / structure interaction will be of major importance.

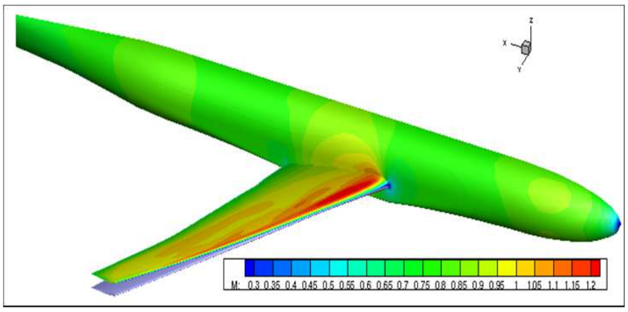


Figure 2: Example of wing deformation (from Onera / DAAP)

The considered aircraft is twin engines airliner, with 310 passengers, with a range of 8 000 nm, a cruising speed of M=0.83. All data provided by Airbus correspond to the XRF-1 model.

5 Development of the multi-level, multi-fidelity coupling

5.1 High Fidelity data to GAP

This side of the coupling is based on the fact that BDP uses high fidelity data, for aerodynamic and structure, providing more accurate results than GAP modules. Therefore, the coupling between both processes aims at improving the reliability of the low fidelity tools. To achieve this objective, the aerodynamic and weight assessment modules of GAP have been modified in order to be calibrated according to the outputs provided by BDP. Moreover, the process should allow a continuous enrichment of the calibration database at each coupling iteration in order to increase the quality of the GAP solution. In that aim, drag data and wing weight (primary structure) are extracted form BDP iterations and post-processed to be integrated in GAP computations. Two possibilities to use BDP data within GAP have been evaluated within ARTEMIS project:

- A preliminary one is based on the correction of incoming data of the BPD using GAP gradient behaviour;
- The second possibility is based on the full of “historical” data from BDP using adapted RSM models.

In the first case, BPD provides the wing primary structure weight breakdown for a given wing planform (B, Φ, e). For the same set of variables, GAP integrate these data and add the wing secondary weights predicted by its own module (see Figure 3).

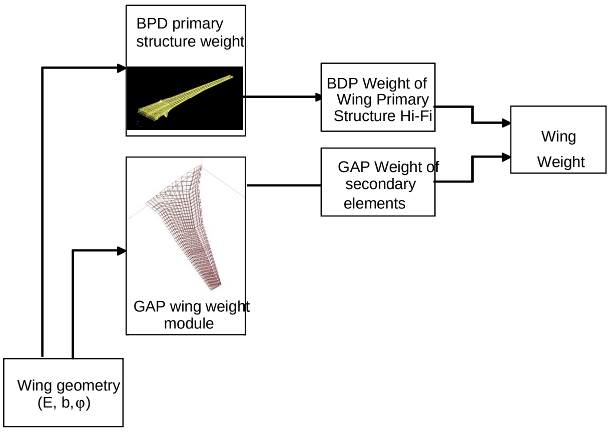


Figure 3 : Wing weight correction in GAP

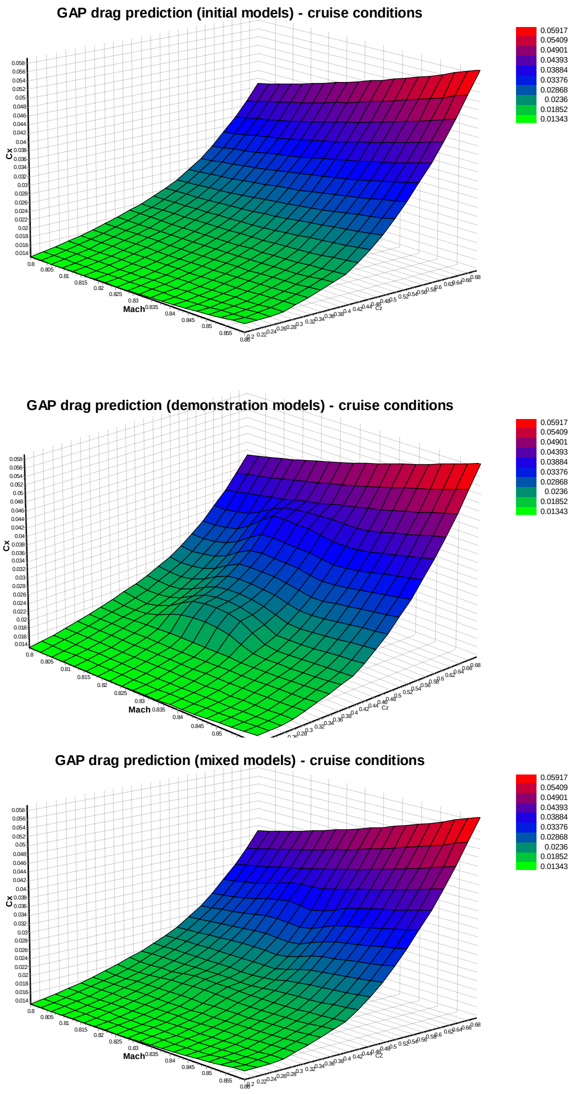
When modifying the planfom variables (V2 demonstrator) within PAG optimisations, the new wing weight consists then in:

- the initial Wing primary structure weight provided by BDP corrected by the evolution of the PAG predictions for the wing primary structure weight between the two sets of planforms;
- GAP prediction of wing secondary weights for the new planform.

Concerning the drag coefficient correction, BPD provides a drag breakdown for the cruise configuration, at C_L = 0.5, for an altitude of 35000 ft and M=0.83. Here, a solution based on models hybridization was considered as the knowledge of wing behaviour during cruise phase was not sufficient to calibrate the GAP aerodynamic modules for the other flight phases (especially the ones at low-speed). Therefore, GAP mixed two models:

- A revised GAP aerodynamic module (Low Fidelity) used for all configurations except cruise;
- A more accurate model, built with information coming form BDP (High Fidelity) in the area of cruise conditions, for C_L between 0.45 to 0.55

A smooth mixing law is used to ensure the connection and ease the use of gradient optimiser. Figure 4 presents some examples of the GAP drag predictions for high Mach number. The 1st carpet plot is the initial low-fidelity model while the 2nd carpet plot shows an example of the mixed models with artificial enhanced differences. Eventually, the last carpet plot is the mixed model used in ARTEMIS, with smaller differences between the 2 components of the mixed models.


GAP drag prediction (initial models) - cruise conditions

GAP drag prediction (demonstration models) - cruise conditions

GAP drag prediction (mixed models) - cruise conditions

Figure 4 : Drag predictions within GAP

Concerning the use of RSM model, the retained solution is to start the process with a reference database provided by each sub-process optimisation of BPD for both the wing primary structure weight and drag coefficient in cruise. Adapted RSM models are built and integrated within GAP process. Then at each PBD loop, several new points are added to the database and the RSM model parameters are re-estimated to increase their accuracy.

5.2 Trade- off information to BDP

This part of the coupling process assumes that the GAP ability to analyze a new aircraft at the conceptual level enables to assess tradeoffs between various disciplines with system level overview. Thus, it can provide some trends regarding the necessary reduction in weight to achieve a certain gain in fuel consumption. In the same manner, it is possible to assess the necessary gain in term of drag to achieve the same improvement in fuel consumption, always considering various disciplines over the complete mission. With such information, the Global Aircraft Process can indicate to the Bi-Disciplinary Process the priority on the discipline to be optimized. As stated earlier, this approach has been implemented in ARTEMIS by introducing a trade-off factor indicated as α and calculated by GAP in the objective function of BDP.

Considering the GAP objective function and the associated BDP objective function, the idea was to investigate the impact of Wing weight and drag coefficient variation on the GAP objective function, around the optimized wing design proposed by the GAP process.

To illustrate this approach, the figure here below below shows the variation of the objective function when modifying the values of W_{wing}, C_D used in GAP.

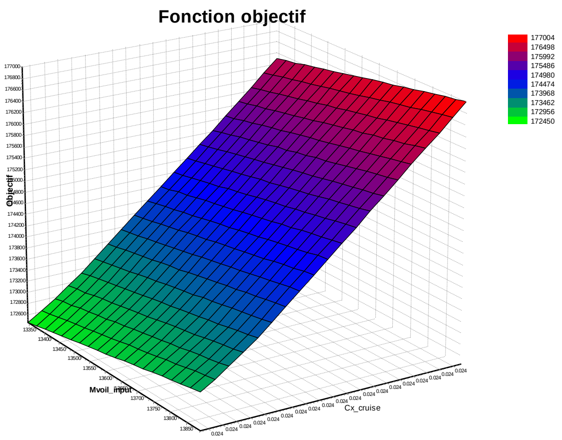


Figure 5 : Behavior of the GAP objective function with respect to W_{wing} and C_D

Thanks to these studies, it has been possible to quantify the equivalences between wing weight variation and a drag coefficient variation as far as the objective function is considered.

Therefore, if α_{Wwing} and α_{CD} are the coefficients related to W_{wing} and C_D in the PBD objective function, they should solve the following conditions,

$$\begin{cases} \alpha_{W_{wing}} + \alpha_{C_D} = 1 \\ \dfrac{\alpha_{W_{wing}}}{\alpha_{C_D}} = \dfrac{\dfrac{dF}{dW_{wing}}}{\dfrac{dF}{dC_D}} \end{cases}$$

One has to note that these coefficients have to take into account the fact that the optimized wing plan form can be found with activated constraints (such as approach speed, for instance).

6 GAP results in ARTEMIS

This chapter presents some results of the multi-level, multi-fidelity and multi-disciplinary with emphasize on GAP outcomes, especially on the validation of the retained methodology.

6.1 Transferring high fidelity data

The results presented hereafter concern the transfer of the high fidelity (BDP) optimization outcomes to GAP in order to improve the validity of the low fidelity aerodynamic and structural models used at the level.

A first result deals with the global impact of a PBD inputs variation on the aircraft mission performance. The next table indicates the impact of a ± 5 counts variation in the cruise drag coefficient. The impact of these C_D variation on the GAP objective function results in a ± 1,2% variation. One has to note that the main part of the variation comes from the fuel burn variation (± 2 000 kilos) which represents the major part of the MTOW evolution. Moreover, the fuel burn variation are mainly issued from the cruise phase. This is logical as these phases represents 95% of the overall mission time (reserve time not included).

Cx_cruise	**Cx - 5pts**	**Cx ref**	**Cx + 5 pts**
MTOW	-1 942	247 914	2 251
Mfuel	-1 935	101 442	1 876
Objective function of PAG	-1 938	174 678	2 063,5

W_{fuel} for cruise	-1 762	85 977	1 716

Table 1 : Impact of BDP aero data on GAP outcomes

Then, one interesting point is to check, for these variations, the behavior of the implemented mixed model presented in section 5.1. Figure 6 presents the beginning of the mission for the 3 aircrafts with the Mach number and drag coefficient evolution in function of time. The climb phase is divided into 2 segments and the cruise phase start at 0.83 mach number and 33 000 ft. The evolution of the Mach number indicates that all 3 aircrafts are performing the same mission. Concerning the drag coefficient, during the climb phase (until 1600 sec.), the differences between the 3 aircrafts are quite small and are due to the initial weight differences, leading to differences in the required C_L (and thus C_D). It confirms that, in this part, the initial GAP model is used. On the contrary, once the cruise phase has been reached, the swap of aerodynamic model occurs and the differences in drag coefficient logically increase between the 3 aircrafts, reaching 7 counts of drag. The remaining 2 counts come from the differences in MTOW as seen in the previous climb phase.

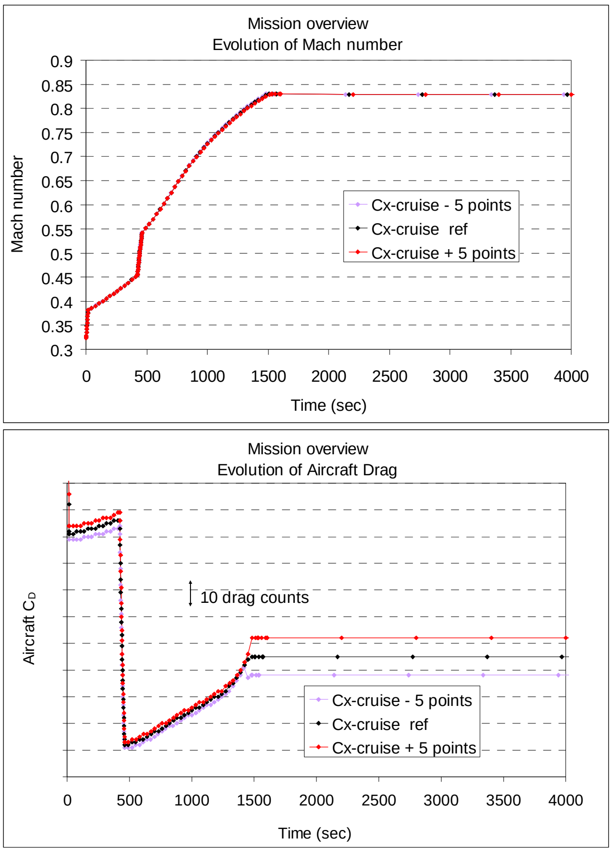


Figure 6 : Mission overview with modification of C_D in cruise.

Therefore, the transfer of the high fidelity (BDP) optimization outcomes to GAP are effective and the model hybridization method is also successful with the swap to the high fidelity database in cruise phase.

Other observations of the results emphasize differences between the various approaches to use high fidelity data. On one hand, the correction is based on few BDP data and GAP gradient while on the other hand; the correction uses only high-fidelity information but requires a bigger database. Figure 7 shows a comparison, for both calibration methods, between predicted evolutions of wing primary structure weight in function of the wing span (B) and the external taper ratio (e). Concerning the wing span evolution, both methods provide trends which assess the good quality of GAP model for this variable.

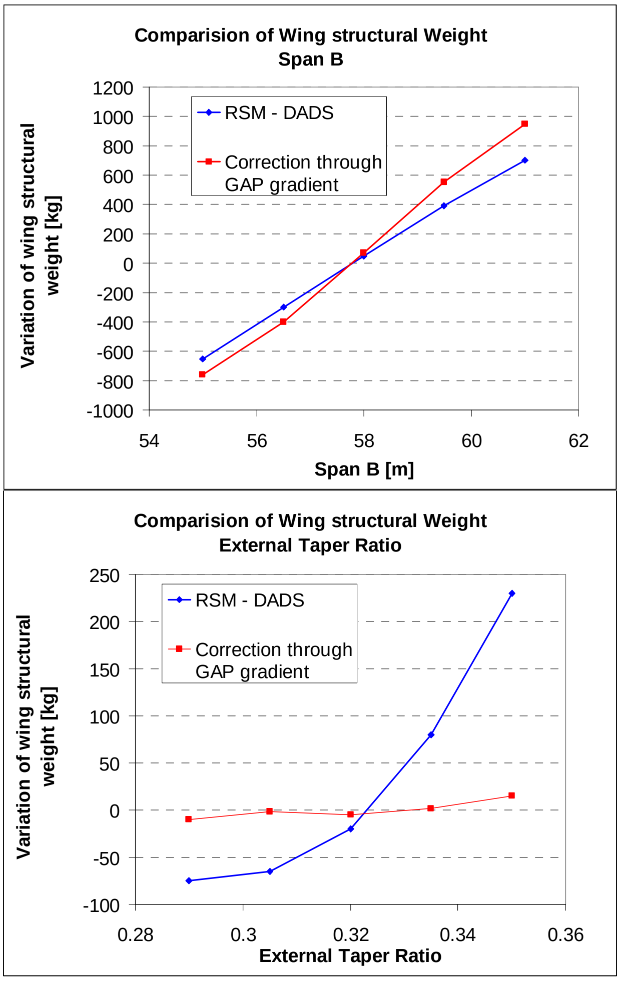


Figure 7 : Comparison of wing structural weight depending on the retained correction methodology (GAP)

Nevertheless, for both wing planform variables, the weights differences between the two methods are close to 250 kilos at the extremum. These values are of the same order as the internal weight variation within the BDP optimization loop. It therefore appears compulsory to retain the methodology enabling the best accuracy of the data transferred from BPD, which means the RSM process.

6.2 Exporting the trade off coefficient

This part of the coupling process assumes that GAP ability to transfer the trend information obtained at complete aircraft level (GAP) to the aerodynamic / structure optimization (BDP).

The example presented here is relative to the V1 demonstrator, where the planform remains unchanged. GAP only performs a new MDA of the aircraft every time the BDP has converged and subsequently provides a new trade off factor. In order to evaluate the variability of the trade off factor, several set of of variables $(W_{wing}, C_D)_{BDP}$ have been extracted from the internal BDP optimization loops and have been used as reference inputs data for the GAP process. Table 2 presents the results for 3 reference configuration that have the same wing planform (same set of B, Φ, e). One can verify that for the same planform, the trade off coefficient α only experiences small variations.

Point	**BDP init**	**BDP iteration 3**	**BDP Iteration 6**
Wwing	*13 618*	*13 852*	*13 683*
PAG Objective	174 750	192 400	175 775
Coefficient α_{Wing}	0,722	0,734	0,732

Table 2 : Variation of the trade off coefficient

Additional tests performed with different planforms shown a higher variation of the trade off factor, but always located in a 0.7 – 0.8 range.

6.3 Performing an optimization a GAP level

These following paragraphs aim at investigating the capability of GAP to provide an optimized configuration taking into account data from BDP. For this step, the design variable ranges have been limited to match the ones used for the BDP:

- $-10\% < \Phi < +10\%$
- $-10\% < e < +10\%$
- $-5\% < B < +5\%$

The reference wing planform and set of high-fidelity data (W_{wing}, C_D) are provided by reference calculations from BDP. The GAP optimization is run using the V2 demonstrator objective function, which contains a penalisation term to avoid searches in a design space that is not compatible with the results of BDP:

$$F = 0.5 \times MTOW + 0.5 \times M_{fuel} + P$$

where P is the penalty term defined as:

$$P = rp.[(e_{PBD} - e)^2 + (B_{BDP} - B)^2 + (\Phi_{BDP} - \Phi)^2]$$

where

- rp is a penalty coefficient iteratively adjusted during exchanges between BDP and GAP
- e_{BDP} is the optimized value of e provided by BDP
- B_{BDP} is the optimized value of B provided by BDP
- Φ_{BDP} is the optimized value of Φ provided by BDP

An initial result concern the impact of the penalty coefficient rp on the optimized solution found by GAP. In that aim, 3 optimizations have been performed, for 3 values of rp : 0, 10 and 100.

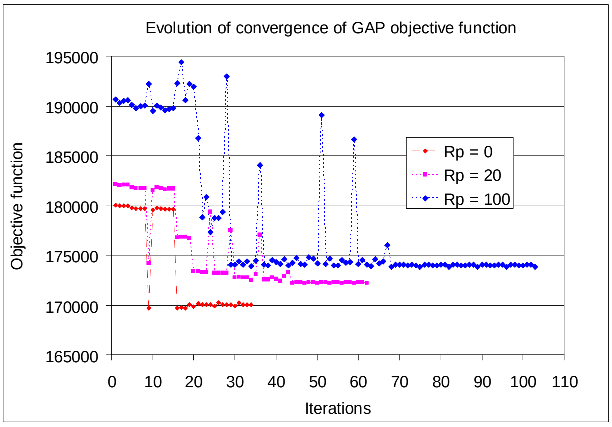


Figure 8 : GAP convergence history

The previous figure shows the convergence history for all 3 optimization: one can check that increasing the penalization term leads to a more difficult optimisation. Anyway, the optimizer always manages to minimize the GAP objective function.

These optimisations have been also the opportunity to assess the evolution of the design variables in percentage of the initial values and the evolution of the constraints in percentage of the maximum values. Figure 9 and Figure 10 illustrates these results:

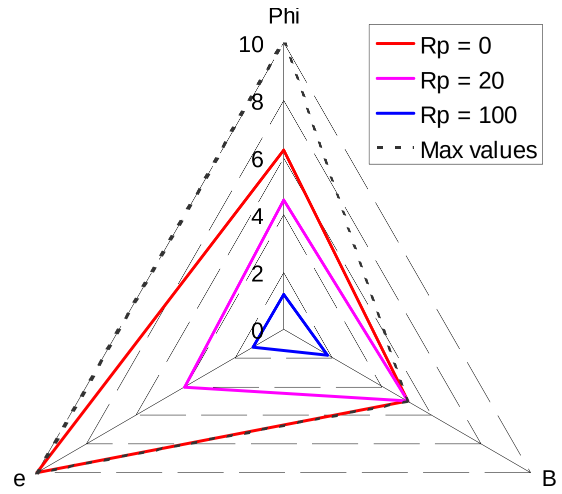


Figure 9 : Evolution of the design variables

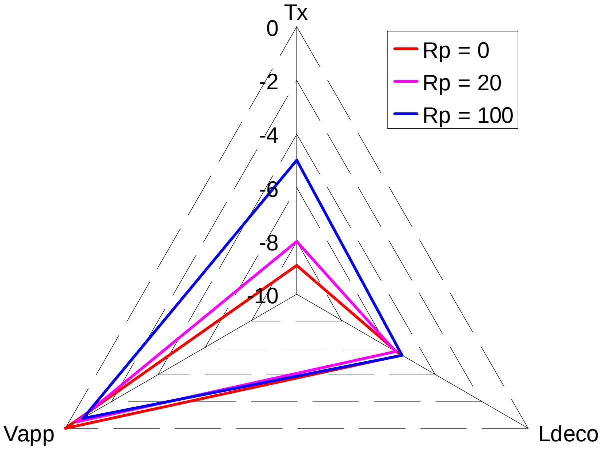


Figure 10 : Evolution of the constraints (Tx indicates the ratio of fuel volume over the tank volume, Vapp corresponds to Landing Speed and Ldeco indicates Balanced field Length)

When the rp coefficient is not activated, the optimizer tends to increase to the maximum limit both the wing span B and the external taper ratio e that are minimizing the objective function without activating the constraints. Concerning the leading edge sweep angle Φ, its evolution is limited to 6% by the activation of the approach speed constraint.

The introduction of the rp coefficient logically restrains the evolution of the wing planform variables. For rp = 10, only the wing span B reaches its maximum value (+ 5%) whereas the other variables only increases by half of the maximum. Concerning the constraints, the approach speed is still activated whereas BFL and wing volume are not much impacted. When using rp = 100, the wing planform variables are prevented from going to far from the reference values and the variation is close to + 2% for the optimised configurations. For this planform, none of the constraints are activated.

Therefore, the penalisation method strongly influences the optimised configuration issued from GAP process. The rp factor and its evolution along the GAP / PBD iterations shall then be carefully defined in coherence BPD for enabling a quick and reliable convergence of the global ARTEMIS process

7 Conclusions

Trying to achieve more and more complex system integration studies and to generate innovative aerospace vehicle concepts, Onera faces the challenge to develop robust, efficient and innovative design methodologies. A large internal investment has been made in the last decades that lead to significant progresses in the field of process set up, high-fidelity tools integration and formal decomposition of the optimization strategy. In that aim, the ARTEMIS project has proved the capability to develop a Multi-level, Multi-fidelity, Multi-Disciplinary Optimization process associated with an operational demonstrator.

At each level, innovative works have been conducted, with for example, within PBD, the challenging use of high fidelity tools in a MDO loop with issues such as the automation of meshes and the management of the large amount of data that have been tackled. More interesting, the investigation made on the coupling process between BPD and PAG has led to explore various solutions to transfer high-fidelity information (BDP) to conceptual design process (GAP) but also to propose a methodology to transfer, using a trade off factor, the trend information obtained at complete aircraft level (GAP) to the aerodynamic / structure optimization (BDP) to identify discipline to promote. These innovative works on coupling activities are a 1st step towards a more automated exchanges between multi level process, what should lead to a quicker and more detailed "aircraft" optimization.

Another key point is that the retained organization of the ARTEMIS process was built to respect the disciplinary autonomy during optimization. This specificity will ease the implementation of the overall process in an industrial context without completely modifying the existing organization.

The ARTEMIS process is now part of Onera MDO tools and is bound to be developed, both from the atomization side to the disciplinary side.

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