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Towards the Industrialization of New MDO Methodologies and Tools for Aircraft Design

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An overall summary of the Institute of Technology IRT Saint Exupéry MDA-MDO project (Multi-Disciplinary Analysis - Multidisciplinary Design Optimization) is presented. The aim of the project is to develop efficient capabilities (methods, tools and a software platform) to enable industrial deployment of MDO methods in industry. At IRT Saint Exupéry, industrial and academic partners collaborate in a single place to the development of MDO methodologies; the advantage provided by this mixed organization is to directly benefit from both advanced methods at the cutting edge of research and deep knowledge of industrial needs and constraints. This paper presents the three main goals of the project: the elaboration of innovative MDO methodologies and formulations (also referred to as architectures in the literature[1]) adapted to the resolution of industrial aircraft optimization design problems, the development of a MDO platform featuring scalable MDO capabilities for transfer to industry and the achievement of a simulation-based optimization of an aircraft engine pylon with industrial Computational Fluid Dynamics (CFD) and Computational Structural Mechanics (CSM) tools.

I. Introduction

A. Motivation

Multidisciplinary Design Optimization appeared in the 80's motivated by the necessity to tackle more and more complex design systems while reducing lead-time and improving robustness as well as accuracy of final design data. There was also an intention to explore more broadly the design space in order to generate innovative concepts and make significant breakthroughs with the current state-of-the-art. This was no more achievable in mono-discipline approaches. It became necessary to implement an integrated methodology from the very early steps and throughout the design process, enabling system designers to handle tight interactions between physics and technologies, and to optimize multiple disciplines at the same time.

While the field of MDO techniques has tremendously grown since then in the scientific community,[1] its applications in industry is still often limited to conceptual design exploration, where it relies mostly on low-fidelity simulations and tabulated data. A major challenge remains to apply MDO techniques to industrial design processes based on high fidelity simulations, handling challenging configurations in terms of geometrical complexity and interacting components, and using many historically separated and sequentially optimized disciplines. The design processes, currently based on complex trade-off studies involving almost

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all engineering disciplines, should however benefit from the potential of most advanced multidisciplinary analysis (MDA) and MDO processes.[13]

Over the last two decades, monolithic (MDF, IDF, All-At-Once), and distributed (BLISS, ATC, CSSO etc.) MDO formulations[1] involving decomposition of analyses that may be coupled, and decomposition of optimizations into parallel disciplinary optimization tasks coordinated by a system-level optimizer,[2, 3, 15] have been proposed. If both appear as appropriate for large-scale design problems, the latter ones are easier to implement in industry since they preserve a partial autonomy of the disciplines,[4] in particular from a software point of view. A promising approach has been developed by ONERA[5] for a wing optimization problem considering a coupling between conceptual and preliminary design phases. The optimization problem associated to the preliminary design phase was handled by the BLISS (Bi-Level Integrated System Synthesis[15]) formulation which constitutes a good track for the work to be done in the MDA-MDO project. This is why a collaboration with ONERA has been set up in the frame of the project on this topic.

However there is no universal method answering all the design problems. The range of possible multidisciplinary decomposition methods is large, and defining the best one is not straightforward. It depends on the structure of the design optimization problem, the dimension of the design space, the type and the number of the objective function, the constraints, and the design variables.

In addition, the problem to be solved commonly evolves in the course of the design study as the knowledge of the problem increases, and the selected methodology has then to be adapted as fast as possible. A challenge is then to have an efficient MDO capability, generic enough to be used in a wide range of industrial applications, while being able to handle specific business constraints and design problems and flexible enough to re-configure easily the multidisciplinary optimization problem. In addition to these technological issues, the preparation and integration of the disciplinary tools and optimization chains are major issues for the implementation of MDO, as it tends currently to take much of the engineering time and cost. This costly work is done each time a new MDO process is achieved in a way that is dedicated to the particular problem under study. This is clearly a blocking point preventing a rapid deployment of MDO methodologies in industry, and making tricky the maintenance of such optimization processes.

B. Overview of the paper

In this communication we first present the MDA-MDO project. Then (in section III), the selection of MDO formulations that are well-suited to industrial constraints is discussed. The GEMS (Generic Engine for MDO Scenarios) library, in charge of building MDO formulations and scenarios, is then presented. This library provides the capability to create a wide range of MDO scenarios in a flexible way. GEMS is the core of a IRT platform that enables to make a link to disciplinary tools and chains and manages data and data configuration. Section IV demonstrates the platform capability while section V presents comparisons between different Bi-level formulations on the academic Super Sonic Business Jet test case. Finally the last section is dedicated to a high-fidelity pylon aero-structural optimization study.

II. The IRT project MDA-MDO

The MDA-MDO project was initiated at the beginning of 2015 at the Institute of Research Technology (IRT) St Exupéry. This project has been funded by the French Agency of National Research, and the industrial partners Airbus, Airbus Group Innovations, Altran Technologies, Sogeti High Tech and CERFACS. IRT St Exupéry is in charge of developing technologies from TRL3 to TRL6 (NASA scale), so takes part to the early phases of MDO methodologies industrialization. Industrial expectations are high, and capabilities have to be demonstrated on test cases that are representative of Airbus' aircraft design problems. The specificity of IRT organization is to build mixed academic-industrial project teams, based on IRT teams together with researchers and engineers seconded from their company. So, the MDA-MDO team also includes researchers from ONERA and ISAE. The goal being to directly benefit from the multiple sources of expertise in advanced MDO methodologies and aircraft knowledge, for the development of innovative and applicable MDO capabilities.

The aim of the project is to develop MDO capabilities including:

- MDO formulations that are compatible with an industrial settings and for which convergence is demonstrated,

- a software library able to build and easily reconfigure MDO formulations; it is a generic engine for building MDO scenarios;
- a MDO platform enabling existing disciplinary tools, chains and workflows to interact with this engine, and providing MDO workflows compatible with High Performance Computing (HPC) environment,

and to apply these capabilities to an aero-structural pylon design optimization test case in the frame of derivative aircraft.

III. MDO formulations

A. Choice of formulations

The objective is to extend the current state-of-the-art formulations in order to make them compatible with an industrial setting: existing tools and framework, types of design variables and types of models. Particular attention is paid to the definition of the different objective functions, constraints, derivatives, (multi)disciplinary analyses, and sub-optimization problems. Existing formulations are modified or hybridized with other ones to meet industrial requirements and to close the gap between the theoretical mathematical assumptions and the industrial tools provided. The equivalence of the newly proposed formulations to initial formulations is investigated as well as convergence demonstrations.

In addition, our purpose is to use MDO formulations in order to solve aircraft optimization problems by considering the variability of a sub-set of components (here the engine pylon) and involving in the multidisciplinary process only a sub-set of disciplines (e.g. aerodynamic performance, loads, structural sizing, mass estimation) but at a higher level of fidelity. It is important to be consistent at the global aircraft level and to keep connected as much as possible pylon detailed information with the global aircraft design. Doing this, the multidisciplinary process can be viewed as:

- optimizing the pylon with a focus on disciplines considered of highest impact on optimization criteria, and for which high-fidelity models are necessary,
- optimizing the pylon in consistency with the whole aircraft but at a lower fidelity, which implies the capability to couple OAD (Overall Aircraft Design) system to high-fidelity disciplines.

In this context, Bi-level decomposition formulations have been selected as suitable for a direct industrial use since they preserve the autonomy of each discipline as it is the case in the current industrial organization.

Separating system-level and disciplinary-level in the problem resolution provides interesting flexibility to the system:

- possibility to solve in parallel the disciplinary optimization problems,
- possibility to use gradient-based algorithms for solving the disciplinary optimization problems, and derivative-free algorithms for solving the system-level optimization problem for which the number of design variables is reduced,
- possibility to make use of different levels of fidelity, depending on the considered stage: MDA or optimization,
- possibility to elaborate a strategy in terms of constraints handling, depending on the considered level.

These Bi-level formulations are easily adaptable to take into account OAD in the optimization process. In such a formulation, OAD may be considered as other disciplines (aerodynamics and structure): OAD shares some design variables with other disciplines, is coupled to them, and provides its own disciplinary design variables. The same objective function is used for all the optimization problems to be solved (either at the system level, or at the disciplinary level, where each discipline optimizes the objective function with respect to its own design variables). This is required to ensure the convergence of the overall optimization process.

Finally, the following criteria are considered to select the MDO formulations:

- be easily extensible to increase the number of disciplines,

- scale well for high-fidelity,
- have good convergence properties,
- be computationally efficient,
- accept minor modifications of the existing tools chains (e.g. aerodynamic optimization chain, structural sizing chain) with respect to the existing modeling levels,
- satisfy coupling constraints at regular points of the optimization steps, in order to obtain a consistent solution in case of premature stop of the process.

Figure 1 presents a simplified view of the Bi-level formulations family selected in the project. These Bi-level formulations are different from the ones of Sobieszczanski-Sobieski and al.:[15]

- Post-optimality analyses are optional, not mandatory when using a derivative-free algorithm at the system level,
- At disciplinary level, truly non-linear optimization problems are solved,
- Disciplinary optimization problems and system-level optimization problem share the same objective function,
- Finally two MDA stages are implemented in order to perform the equilibrium between the disciplines: one before the disciplinary sub-optimizations and one after them, making then use of the optimal disciplinary design variables. This enables to launch any optimization (disciplinary sub-optimization or system-level optimization) from a consistent solution.

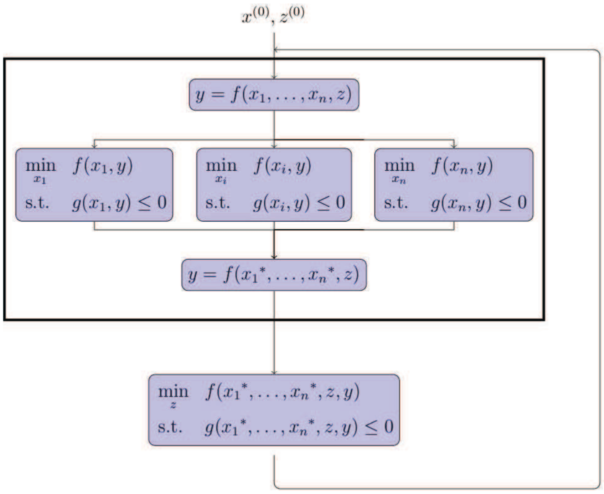


Figure 1: Bi-level formulation

These formulations are being validated by applying the following approach:

- First, a thorough comparison of these formulations is done on test problems in terms of results and performance.
- Second, these preliminary results bring out recommendations to make decisions when solving more complex aero-structural test cases.

B. The Generic Engine for Mdo Scenarios (GEMS) library

The MDO formulations engine GEMS is responsible for managing the MDO scenarios, including the optimization problem (objective function, constraints, coupling variables, design variables) and optimization algorithms. The MDO formulations engine is independent of all disciplinary tools and thus can be used for any test case. It orchestrates the execution of the processes according to the needs of the algorithm (optimization or Design Of Experiments algorithm). It is in charge of the MDO formulation of the problem and links the mathematical methods to the simulation software. The GEMS software was inspired by πMDO,[14] OpenMDAO,[12] as well as by WORMS, Optalia and OpenDACE projects from Airbus.[16, 17]

It can be interfaced with multiple workflow engines, typically in charge of chaining elementary processes across multiple machines within disciplines, such as aerodynamics and structure simulations. The package is developed in Python, since it is a glue language, which can be easily interfaced with many other languages. Besides, a focus on multi-level formulations implementation is made in GEMS, in addition to the easy interfacing with black-box industrial optimization chains. These are significant differences with the OpenMDAO library,[12] which, in the last versions as of 2016, is more focused on obtaining the most efficient implementation of monolithic formulations such as MDF. Monolithic formulations such as MDF and IDF are also available in GEMS, but the focus is put on the capability to integrate off the shelf simulation workflows, and to easily reconfigure the overall MDO process rather than on the pure computational performance.

The MDO formulations engine triggers the execution of simulation software or chains of simulation software when requested by the optimization algorithm. A MDO formulation and the simulation software execution are interfaced through mathematical functions. The functions are called by the optimization algorithm with new design variables values (typically system design variables, coupling variables or operating conditions). This update of design variables must impact the simulation software (it must therefore be parametric) and return the values of interest, ie objective functions or constraints.

A focus on optimization algorithms is also made, which have a strong link with MDO formulations, since both are splitting optimization problems into sub-optimization problems. In particular, methods to distribute a monolithic optimization problem by splitting their design space are developed and integrated in GEMS. Two approaches are considered to build such processes that distributes the optimization problem:

- Use a bi-level MDO formulation that builds a set of sub-processes to be executed and orchestrated by a system-level process

- Use a domain decomposition algorithm that splits the design space of a monolithic optimization problem in order to build multiple sub-optimization problems that are synchronized.

Besides, multi-level MDO formulations imply the multiple resolutions of the same disciplinary optimizations with different shared design variables. Then, optimization algorithms that are able to recycle information between two resolutions are also developed in the project.

A key advantage of this approach is that the MDO formulations can be validated on academic test cases, for which solution is known and run time is short. The high fidelity test cases taking hours to run, the classical trial and error cycles times are prohibitive in MDO, since hundreds of simulations are required to test a formulation. Besides, the integration of the disciplinary tools can also be tested separately. MDA, or coupling methods such as Gauss-Seidel, Jacobi, Quasi-Newton variants, or hybridized algorithms are also implemented in our platform and compatible with black-box software. When analytical Jacobian matrices of the disciplines are available, automated discrete adjoint, direct or reverse mode for calculation of the coupled derivatives is possible.

Finally, tools to analyze the optimization results and visualize the design space are implemented within GEMS or interfaced with it.

IV. MDO platform concept

A multidisciplinary software platform is required to address industrial-scale MDO problems through an easy creation of multidisciplinary processes. The goal is not to develop once more a specific workflow engine solution that would be appropriate for MDO data flows and MDO processes, but to make use of a range of single-discipline design optimization tools suites and frameworks that are already at a mature level in the industry and have proved their efficiency in mono-disciplinary design optimization. The advantage of this pragmatic approach is not only to build faster MDO processes but also to be well-adapted to industrial organization where disciplinary design tools development is traditionally managed by separate departments having each their own tools development strategy and life cycles. However the number of possible workflow engine solutions is large and their use in industry is often versatile; easily interfacing with a new disciplinary design process and workflow is then a strong requirement for the MDO platform.

The targeted disciplinary processes that have to be embedded in the MDO processes are based on both low fidelity models such as semi-empirical formula or surrogate models and high fidelity simulation such as CFD and CSM. Distributed computations on machines of different operating systems is a key point to be handled by the platform, together with efficient links to HPC environments.

The MDO platform provides a MDO user with the capability to develop new MDO formulations, integrate new domain disciplines, build MDO scenarios, run and monitor these scenarios and finally analyze and visualize the MDO results.

The core of the platform is the GEMS library, responsible for managing the MDO scenarios including design objectives, constraints, coupling strategies, DOE and optimization algorithms. The key challenge of the platform is to establish a link between the generic engine of MDO scenarios and the disciplinary tools and workflows while enabling a fully automated execution of these tools.

Moreover, although the use cases studied in the project are aircraft components optimization, the MDO formulations engine we are developing shall be capable of addressing a much broader class of use cases, from analytic and academic use cases to industrial systems optimization, using a large variety of numerical models and algorithms.

The platform architecture is a component-based architecture, the assembly of components depending on the design problem to be solved. Each component having the possibility to evolve separately and to be used independently or in different contexts, the configuration management is key for ensuring the maintenance, testing and deployment of the whole or parts of the system.

An overview of the main software components of the platform is shown in fig. 2. The central role of the formulations engine clearly appears on the diagram, as a glue between simulation software in their workflow engines and the mathematical algorithms such as optimization algorithms.

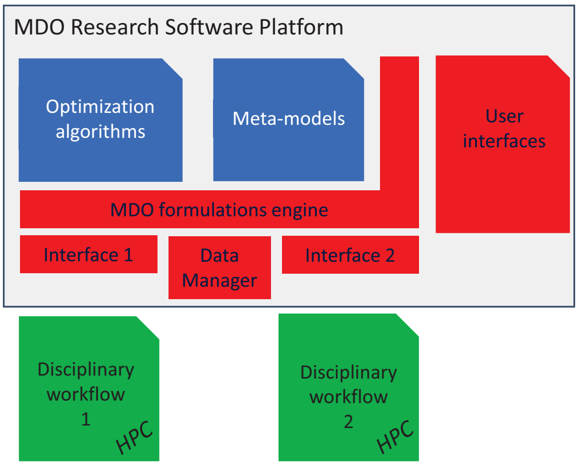


Figure 2: Architecture of the MDA MDO platform

V. Demonstrator on Sobieski's SSBJ use case

A. Test case presentation

In this section, we demonstrate the platform infrastructure capability on the academic Super Sonic Business Jet (SSBJ) test case.

This test case was taken from the reference article by Sobieski, the first publication[15] on the BLISS98 formulation. It is based on a 1996 AIAA student competition organized by the AIAA/United Technologies/Pratt & Whitney Individual Undergraduate Design Competition. The main reasons for the choice of this academic test case is its availability, the fact that it is standard in the MDO community, and the similarity of the problem structure with the targeted high-fidelity pylon optimization test case.

The formulas used for each discipline are based on semi-empirical and/or analytical models. The aim of the problem is to maximize the range of a SSBJ under various constraints. The problem is built from three disciplines : structure, aerodynamics and propulsion. A fourth discipline, weakly coupled to the other ones, is used to compute the range of the aircraft on the mission.

B. Bi-level formulation identification

In this section we present three different Bi-level formulations and compare them with the standard MDF one. Using the Extended Design Structure Matrix (XDSM) representation developed by Lambe and Martins,[11] it is easy to compare the different process organization in the different formulations.

Figure 3 displays the MDF formulation applied to the SSBJ test case, generated using the XDSMjs library from ONERA[26] . Figures 4, 5 and 6 show three different Bi-level formulations. Notations are different in Figure 3, which displays the physical quantities, from the other figures, which display the variables names used by the numerical resolution process.

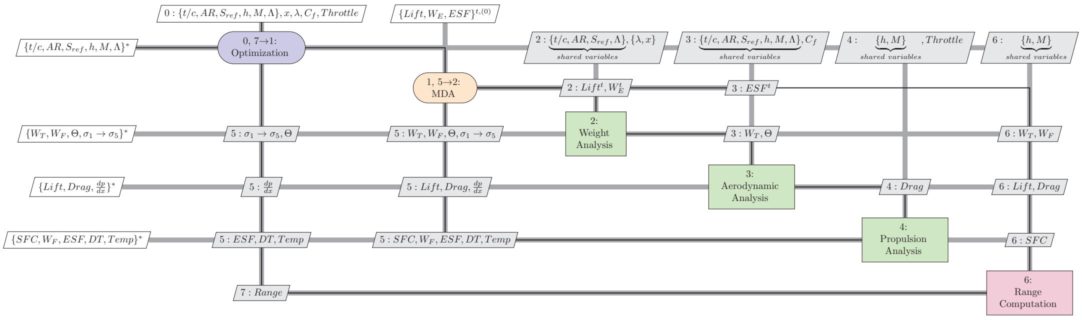


Figure 3: MDF formulation applied to the SSBJ test case

On Figure 4, the system-level optimization problem maximizes the range objective function with respect to shared design variables while disciplinary level optimization problems optimize their specific contribution: structure maximizes $\ln\left(\frac{W_T}{W_T - W_F}\right)$, where W_T is the total aircraft mass and W_F is the fuel mass, aerodynamics maximizes lift over drag ratio(L/D) and propulsion minimizes the Specific Fuel Consumption (SFC), with respect to their own disciplinary design variables, under their own constraints. In this particular case it is legitimate to optimize different objective functions since contributions of aerodynamics, structure and propulsion to the computation of the range are separable as it can be seen in the Bréguet equation:

$$\text{Range: } R = 661\sqrt{\theta}\ \underbrace{\frac{L}{D}}_{\text{Aerodynamics}}\ \underbrace{\frac{1}{SFC}}_{\text{Propulsion}}\ \underbrace{\ln\left(\frac{W_T}{W_T - W_F}\right)}_{Structure} \tag{1}$$

where θ is a temperature ratio defined by a standard atmosphere:

$$\text{Temperature ratio: } \theta = \begin{cases} 1 - 6.875 \times 10^{-6} h & \text{if } h < 36089\ ft \\ 0.7519 & \text{if } h > 36089\ ft \end{cases} \tag{2a}$$

On Figure 5, all problems maximize the same objective function that is here the range. In the general case, this formulation uses the same objective function and constraints as the original monolithic optimization problem. On Figure 6, the coupling between disciplines is introduced at disciplinary levels in addition to the system-level MDA stages already involved in this Bi-level formulation. The figure only shows the sub-scenarios of the Bi-level formulation since the system-level scenario remains unchanged compared to the second Bi-level formulation. In such a way, each disciplinary optimization sub-process is implemented with its own MDF formulation, making finally this Bi-level formulation a distributed MDF formulation. This formulation offers the possibility to choose different levels of coupled modeling, depending on the considered sub-process. It is particularly well-adapted to concrete high-fidelity aero-structural optimization problems where flexibility effects are important. In such cases, the idea is to use high-fidelity aero-structural coupling for the system-level MDA stages, to use lower level of fidelity for the structure model to be coupled to aerodynamics within the aerodynamic optimization sub-process, and to use lower level of fidelity for the aerodynamic model to be coupled to structure within the structural optimization sub-process. It is also possible to introduce a MDF formulation only for one disciplinary optimization sub-process and not for all of them. Finally, this Bi-level formulation offers a high level of flexibility that makes it the good candidate to be applied to the high-fidelity pylon aero-structural optimization test case.

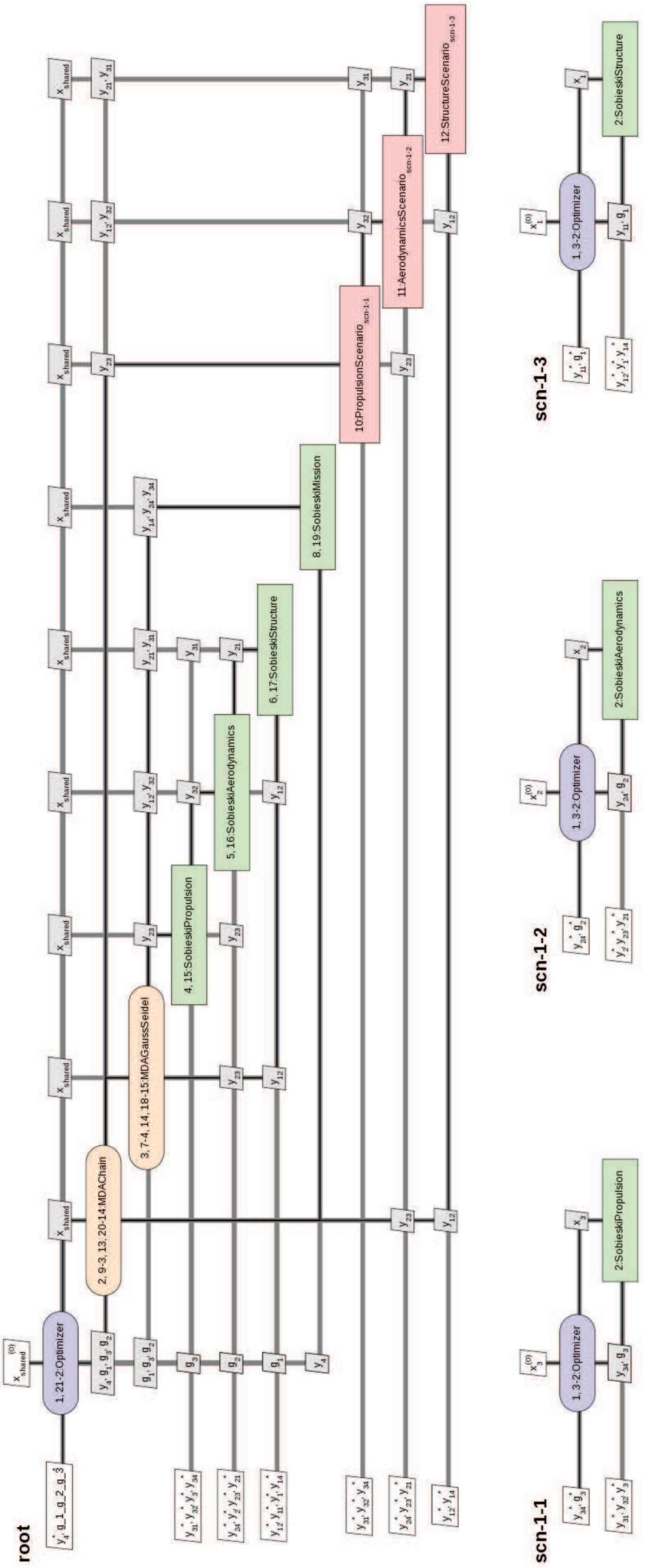


Figure 4: First Bi-level formulation applied to the SSBJ test case

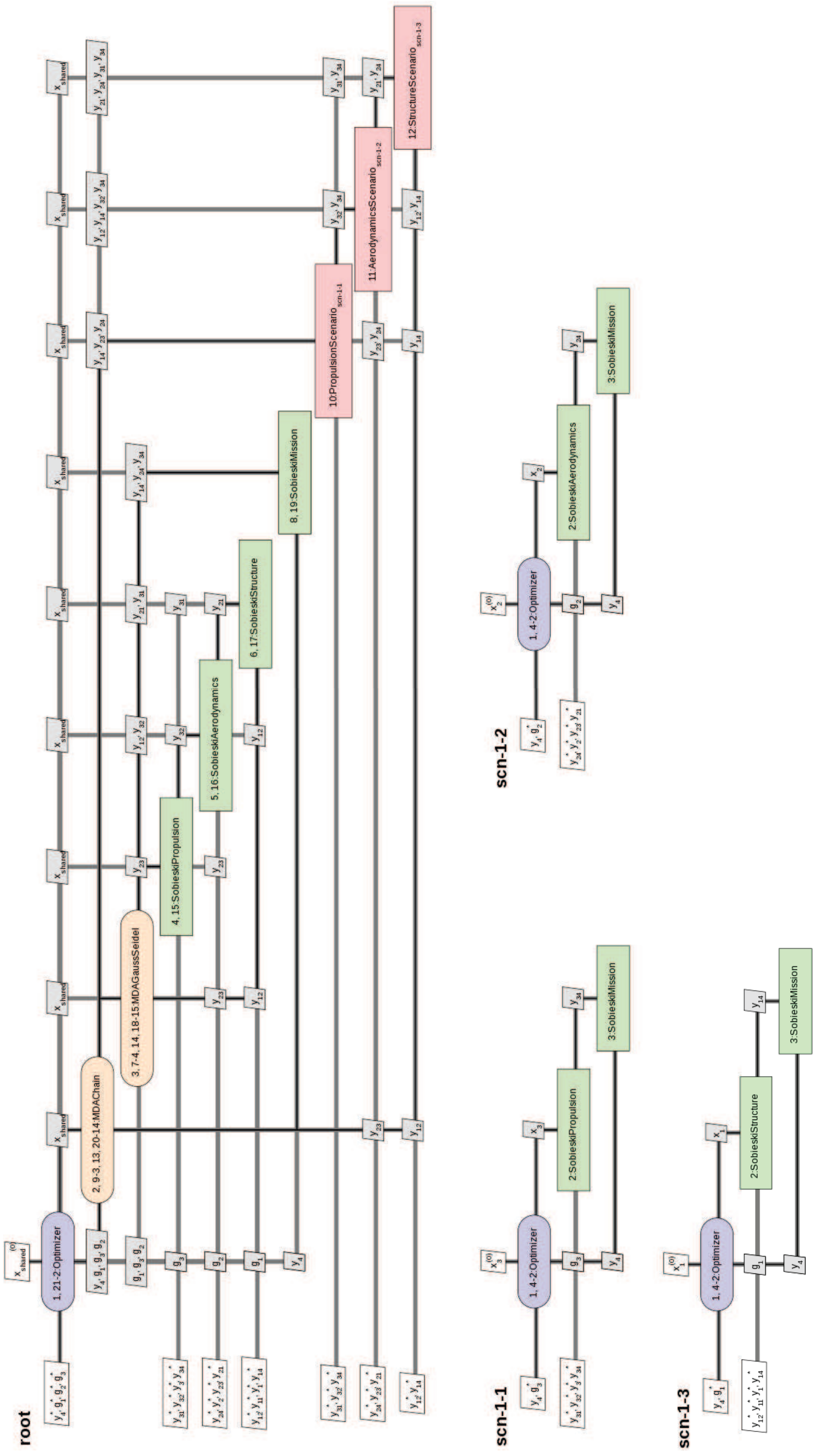


Figure 5: Second Bi-level formulation applied to the SSBJ test case

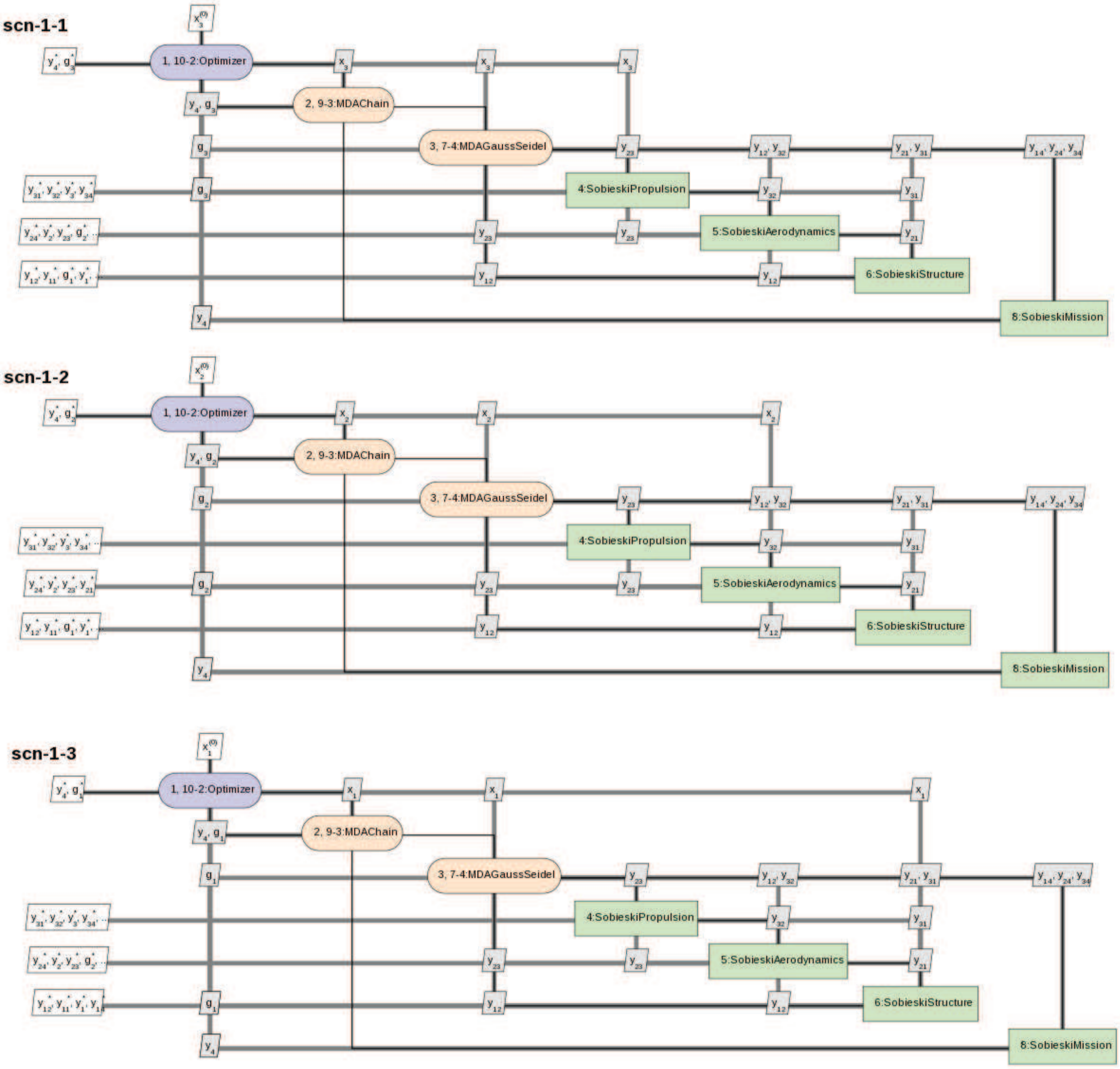


Figure 6: Sub-scenarios of the third Bi-level formulation applied to the SSBJ test case

C. Platform setup

The main challenge of this test case is to test the platform infrastructure. Therefore, a classical MDO formulation is used, here MDF, but the different disciplines of the test case will be called through different workflow engines and on different machines :

- The Structure discipline is wrapped in *Model Center*®, and executed on a remote *Windows Server*® machine through a job scheduler.
- The aerodynamics discipline is wrapped in a proprietary workflow engine from Airbus based on Eclipse RCP,[19] typically used to chain aerodynamics software, under a Linux OS.
- The Mission discipline is wrapped in a Scilab[18]-based Airbus software typically used to manage overall aircraft design, under a Linux OS.
- The Propulsion discipline, wrapped directly in GEMS, in Python, under a Linux OS.

D. Numerical results

The MDF formulation is first applied to the SSBJ test case. The Cobyla[9] algorithm is used to solve the MDO problem, with a Gauss-Seidel algorithm to solve the multidisciplinary analysis step. The range function is maximized, and the theoretical optimum of 3963 nm is found, as shown in Figure 7. The Cobyla derivative-free algorithm is used because using coupled derivatives is not always possible. They may not be available in the business tools, or may not exist, for instance in case of discrete variables such as composite stacking or material choice. All these reasons apply to the test case described in section VI. However aerodynamic derivatives are available for the latter test case; to reflect this, the gradient-based SLSQP[10] algorithm is used in the disciplinary optimization of the SSBJ test case.

Figure 8b displays the inequality constraints versus the iteration of the algorithm. A symmetric log scale is used, so that constraints with different orders of magnitude can be displayed with the same color map. Each line of the plot is colored by the value of a constraint, in red if the constraint is violated, green if it is satisfied, and white if active. At the end of the execution, all constraints are satisfied. Figure 8a displays the value of the design variables, in a similar way as Figure 8b. All variables are scaled between 0 and 1, with respect to their bounds. These plots are automatically generated by the GEMS library; they enable a fast visual analysis of the optimization history.

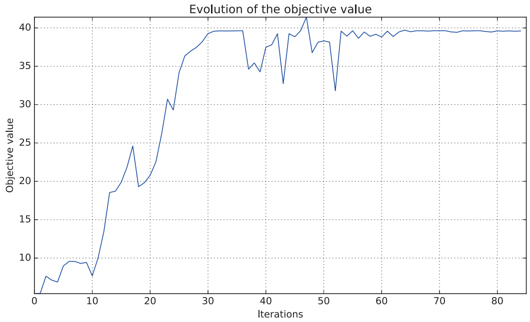


Figure 7: Objective function history for the MDF formulation

Then the three Bi-level formulations are applied to the SSBJ problem. The Cobyla algorithm is used at the system-level while a gradient-based algorithm is used to solve the disciplinary optimization problems. The three formulations allow to reach the theoretical optimum. The constraints are satisfied by sub-solvers at each system iteration. This is an interesting property because the process could be stopped before convergence and still provide a satisfying solution from an engineering point of view.

These formulations are compared in terms of evolution in the course of the system-level iterations of the objective value (figures 9, 11 and 13), evolution of design variables(figures 10a, 12a and 14a), evolution of inequality constraints (figures 10b, 12b 14b).

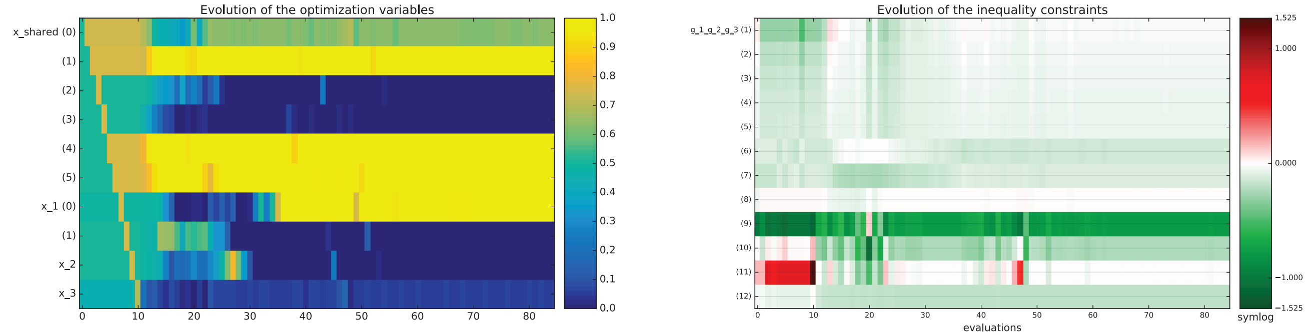


Figure 8: Design variables and inequality constraints history for the MDF formulation

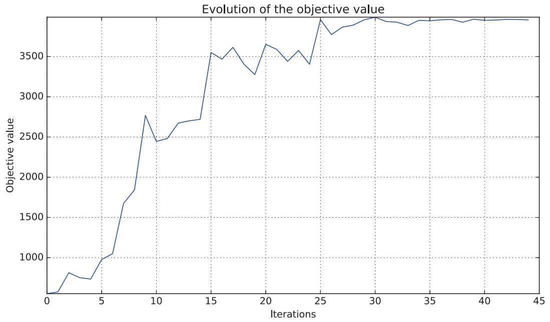


Figure 9: Objective function history for the first Bi-level formulation

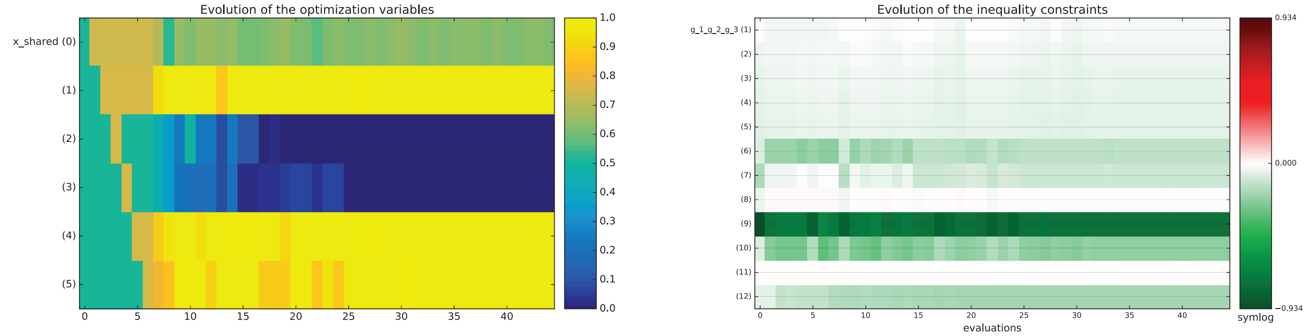


Figure 10: Design variables and inequality constraints history for the first Bi-level formulation

The table 1 presents the number of evaluation calls for each MDO formulation, which characterizes their respective efficiency.

This SSBJ example shows the better efficiency of the first and second Bi-level formulations compared to the reference MDF formulation and the third one for which the number of disciplines calls is very large. The second Bi-level formulation will be adopted for the high-fidelity pylon optimization test case (see section VI). It has to be noted that the number of calls includes all disciplines whatever their level of fidelity; it would be better to take into account only the high-fidelity discipline calls, the low-fidelity disciplines being much cheaper. With such correction, the efficiency of the third Bi-level formulation would be improved.

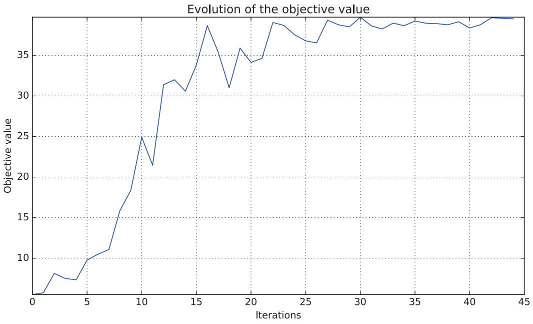


Figure 11: Objective function history for the second Bi-level formulation

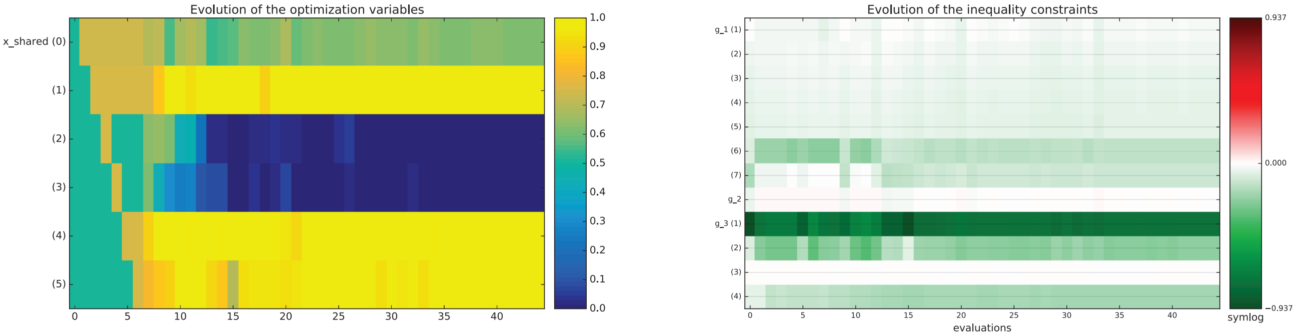


Figure 12: Design variables and inequality constraints history for the second Bi-level formulation

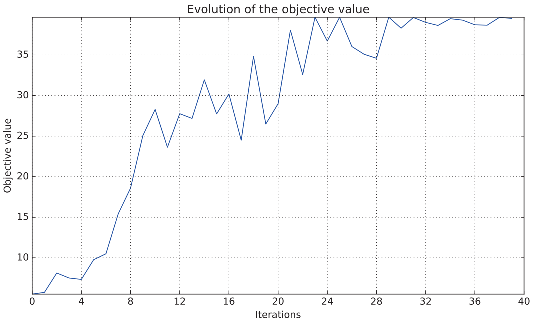


Figure 13: Objective function history for the third Bi-level formulation

This third Bi-level formulation could also be improved through some modification where only a sub-part of the disciplines would be optimized through a MDF formulation at the disciplinary level. This formulation would then become an asymmetric hybrid Bi-level formulation.

Finally, the MDF formulation using coupled derivatives and a gradient-based optimization algorithm leads to a better efficiency than these Bi-level formulations; but, as explained above (D), such conditions are very demanding and in general not compatible with industrial tools and settings.

This test case validates the GEMS library flexibility, enabling to switch easily from one MDO formulation to another one, ensuring automatically the required consistency between the inputs and the outputs. It

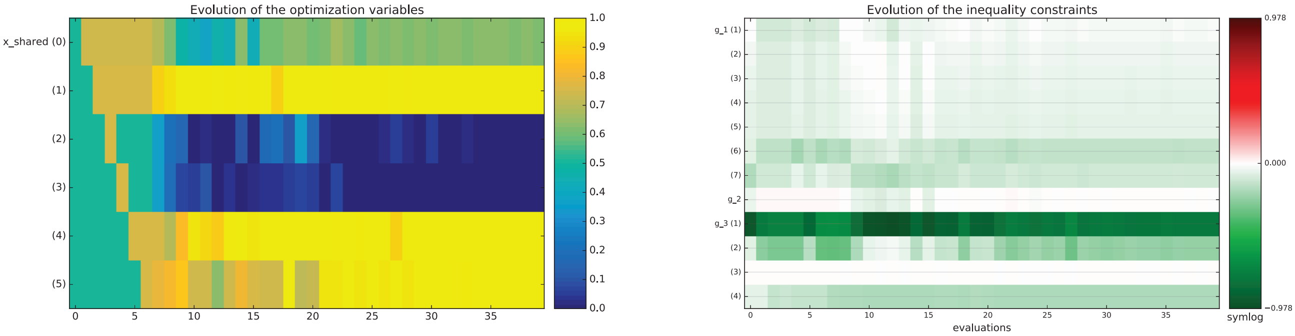


Figure 14: Design variables and inequality constraints history for the third Bi-level formulation

Table 1: MDO formulations comparison

MDO formulation	MDF	Bi-level 1	Bi-level 2	Bi-level 3
Number of calls to disciplines	2623	1434	1966	13035

also validates the platform infrastructure, which enables the execution of a MDO process driven by an MDO formulation in the GEMS library, while executing black-box software of different natures: proprietary, commercial or open source, in multiple machines under Linux or *Windows Server*® operating systems.

VI. High-fidelity pylon aero-structural optimization test case

This section is dedicated to the study of the pylon aero-structural optimization in the context of aircraft re-engine.

In this test case, the Airbus XRF-1 transport aircraft configuration is used as the reference geometry. It is a generic research configuration based on a typical Airbus aircraft design. Airbus developed and provided this configuration together with a set of models (geometry (see Figure 15, in blue the components wing-nacelle-pylon considered in this test case), load cases, finite element model, mass distribution data, beamstick model and doublet lattice model) in order to facilitate the assessment and development of research MDO capabilities.

Figure 15: XRF-1 CAD (Computer-assisted design) geometry (for the flight shape)

Aircraft re-engine generally consists in replacing current engines of an aircraft family member by more powerful ones or, more frequently, by new generation engines providing a significant improvement in terms of Specific Fuel Consumption (SFC). This improvement in SFC is generally associated with an increase of maximum thrust. In any case, the re-engined aircraft is supposed to offer a more attractive set of performances for the airliner.

This type of new engine is characterized by larger pylon and nacelles making the power plant integration challenging. The fairing shape and stiffness design of the pylon is multidisciplinary in essence, and has to tackle strong geometrical layout constraints as well as aero-elastic and aerodynamic interactions with wing and nacelle. A multidisciplinary compromise drives the pylon shape design. Both structural weight and wing aerodynamics are affected by the pylon width and height. For instance, fan blade out events generate very large loads on the pylon and are consequently critical sizing failure cases of the structural elements. For given loads, a larger pylon reduces stress constraints and therefore primary structure weight. On the other hand, a larger pylon can negatively affect the wing aerodynamics, at the point that it can require a redesign of the wing.

In this test case, MDO capabilities are used in order to assess the impact of such new engine on the global aircraft performances. The expected results are a trade-off study of the aero-structural pylon, with respect to a set of shared parameters such as width and mount position, the overall process being defined by a bi-level MDO formulation taking into account overall aircraft constraints.

For achieving it, several challenges have to be addressed:

- complex geometries involving many intersecting elements that are affected by the parametrization
- very large aerodynamic meshes
- important number of constraints from various nature (mostly industrial constraints)
- the need of consistency between the aerodynamic CAD model and the structural CAD model

A. Overall aircraft design (OAD)

The OAD contribution highly depends on the set of degrees of freedom that are let open for design activity. Examples of OAD parameters are: engine size, nacelle geometry and position, pylon overall geometry, wing planform and movables geometry, horizontal and vertical plane tail geometries, and characteristic masses such as Maximum Take-Off Weight, Maximum Zero Fuel Weight, Maximum Landing Weight, Max Fuel Weight, Operating Empty Weight, Manufacturer Empty Weight.

In a re-engine operation, not all degrees of freedom are available, and in this test case the design space is restricted as follows:

- The wing geometry is supposed to be fixed, which means:
  - Y-wise pylon to wing attachments are fixed,
  - a possible reinforcement of the wing internal structure is considered,
  - a possible re-twist is considered in order to optimize the installation drag.
- The engine comes off the shelf, which means:
  - the diameter is fixed,
  - the attachment points are fixed in reference to the engine itself,

In principle, OAD can be linked with the aero-structural pylon optimization process at four different levels:

- Providing the common objective function for all embedded disciplines, here the Cash Operating Cost (COC); this is a prerequisite to ensure the consistency of the Bi-level formulation;
- Similarly, computing shared overall performance constraints such as take-off field length, maximum approach speed, operational climb ceilings etc.
- Delivering consistent characteristic weights for a given nominal range;

- Managing internal design variables to optimize the same objective function as the other disciplines in the process. In general, OAD design variables are selected to recover an acceptable situation after some operational or Handling Quality constraints have been identified as active. Classical design variables are horizontal tail and elevator areas and maximum deflection, vertical tail area, rudder area and maximum deflection.

In the first stage of this test case, the three first levels of coupling are considered. However, since the OAD discipline has no disciplinary design variables, the performance constraints may not be satisfied. In a more advanced test case, OAD variables such as horizontal and vertical tail planes geometries, or engine size could be introduced in order to satisfy these performance constraints.

B. Aerodynamic optimization

1. The aerodynamic optimization within the MDO process

The aerodynamic process is one of the two disciplinary optimization problems, together with the structural one, in the Bi-level formulation of the present study. They occur after the first MDA phase. When system design variables are updated by the system level optimizer, and for given coupling variables, the disciplinary aerodynamic shape optimization process shall minimize the contribution of the aircraft aerodynamics to the system objective function (defined in this test case as the COC), with respect to the private aerodynamic shape variables. Such variables control the detailed shape of the pylon. The shape shall respect several geometrical constraints. It shall fit in the structural pylon box, and allow the presence of the systems (such as oil and fuel systems, fire suppression, or air bleed), which are numerous in the pylon. This is a challenge since the aerodynamic and structural parametric shapes are independent with respect to their private design variables. The system design variables shall then contain sufficient information to ensure the geometrical integration constraints.

Usually, aerodynamic optimization processes minimize the drag of the aircraft at constant lift. However, the system optimization having the COC as objective function, and being subject to performance constraints also depending on aircraft aerodynamics (minimal climb performance for instance), this traditional approach is not suitable for the bi-level process, because it may generate inconsistency between the design objectives. The minimal drag shape may not satisfy climb performance, or may not be a minimal COC shape. The fuel burn is a key contributor to the COC, concerning aerodynamics. It depends on the aerodynamic forces encountered during the whole flight, and therefore the formulation of the aerodynamic optimization problem is based on a multi-point optimization. In order to select the required operating conditions for the COC minimization, the Gradient Span Analysis[21] (GSA) algorithm is used. This ensures mathematically that no COC gain opportunity is missed due to a missing operating condition in the optimization problem; and that the CPU cost is minimal because no extra operating condition is incorporated. The objective function being the COC, which is directly computed from the drag at the multiple operating conditions, there is no need to aggregate the objectives by specifying weights associated to these operating conditions, which is a difficult task.

2. Process and tools setup

The aerodynamic optimization process consists in 5 main steps:

- The shape parametrization, based on a parametric CAD engine
- An analytic volume mesh deformation
- The resolution of flow direct and adjoint equations using the elsA CFD solver[22]
- A post processing step to compute aerodynamic forces and moments
- An overall aircraft simulation that simulates the aircraft mission and computes the optimization criteria (COC, and operations performance constraints such as Takeoff field length).

All these steps are fully differentiated, either by hand or using automatic differentiation, in order to provide derivatives of the objective function and constraints to the optimization algorithm. The discrete adjoint method is used in the CFD solver to compute these derivatives at an affordable cost. Then, the derivatives are propagated in reverse mode. For more details about the process, see,[16] pages 81-100.

3. The shape parametrization

The pylon, which connects the engine to the wing, is a complex shape in terms of topology. It intersects with the wing and multiple parts of the engine, such as the nacelle, the fan and the nozzle exhausts. Figure 16 displays the engine mounted on the XRF1 wing, with the pylon-nacelle-engine intersection lines computed by the CAD model.

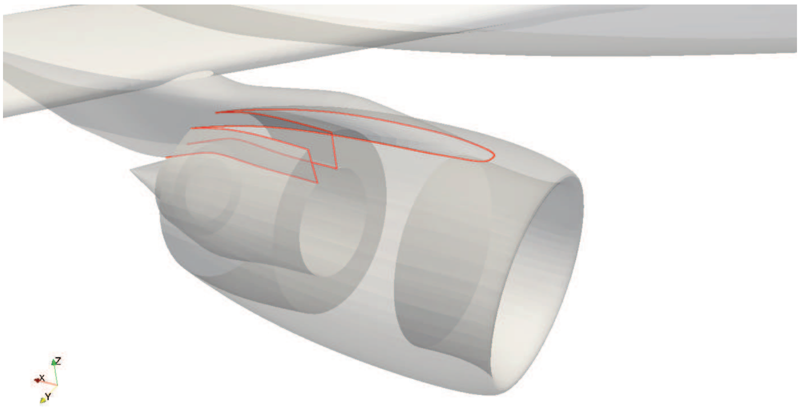


Figure 16: The engine CAD intersections with the pylon

When the pylon CAD is modified by the parametrization, these intersections shall be computed accordingly, in order to be able to deform the surface mesh in a consistent way. This imposes to make the nacelle mesh slide on the nacelle CAD according to the nacelle-pylon intersection displacement for instance. Figure 2 illustrates the deformation field generated by a 500 mm forward displacement of the nacelle. Figure 3 shows the updated model after the deformation.

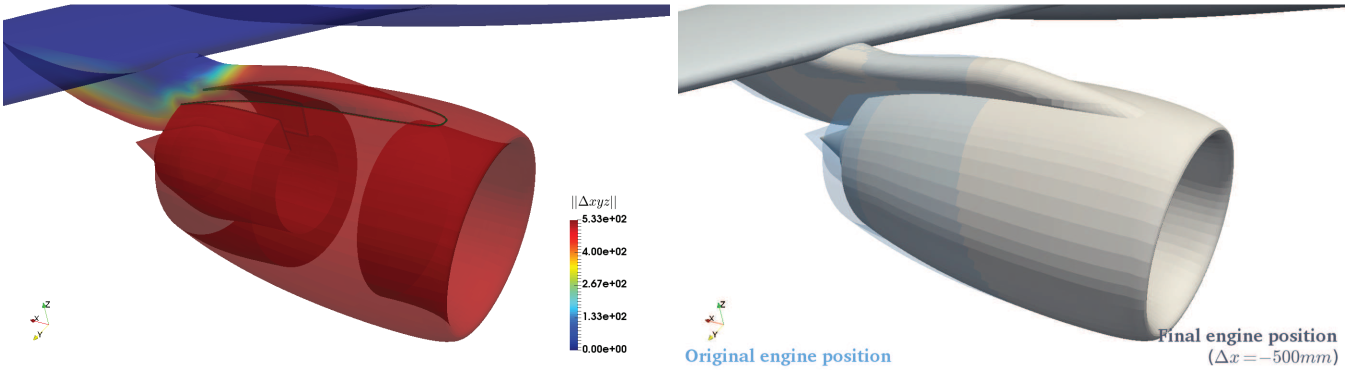


Figure 17: Surface mesh deformation and deformed CAD due to engine forward displacement of 500mm

C. Structure optimization

This discipline is associated with a process and a related workflow designed for providing information such as the mass or the stiffness of the primary structure involved in the overall MDO process using shared parameters with other disciplines. This workflow integrates Airbus tools. The use of Airbus tools is a very important requirement for the project. It will not only help the integration of the chain in an industrial environment and give to the optimization results a real industrial meaning but it will also prove that the platform will not be intrusive and that it will be generic enough to be usable by industrial stakeholders.

1. Workflow description

Before optimizing the engine pylon, some model generation is required. We can decompose the workflow in 4 main steps: geometry generation, finite element model creation, load computation and sizing process. Firstly, the workflow has to generate parametric geometry. Two Airbus tools, PARMOS and FEMIX-CATIA, are used to generate respectively the external shape and detailed geometry of an aircraft structure.[23] Both of them are using templates which are customized upfront for each design concept choice. Once they have been built, a non-expert user can generate as many as different pylon architectures he wants. Depending on the design choice, several levels of fidelity can be easily modelled. Moreover, the generation of parametric finite element models is carried out by FEMIX-SIMX, another Airbus tool, providing the link with rapid sizing tools used for many different components such as wing and fuselage.

Figure 18 presents the bi-step FEMIX modelling process.

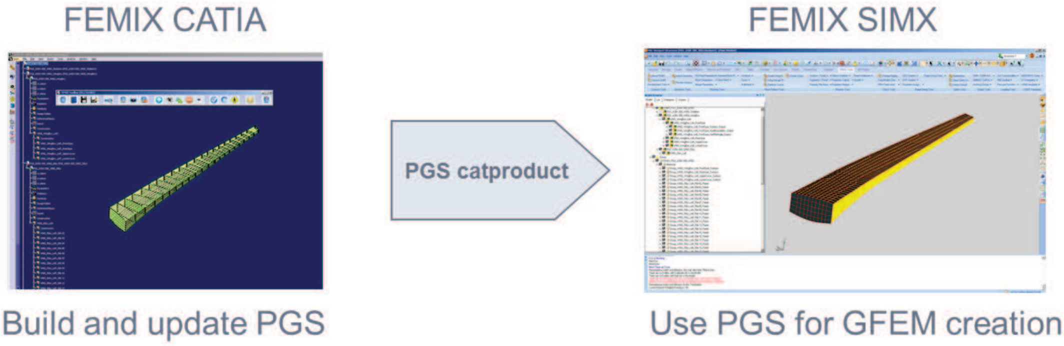


Figure 18: FEMIX: a bi-step modelling process able to parameterize a structural concept and generate finite element model and stress model for sizing.

FEMIX-SIMX does not only mesh the pylon geometry and set properties. It also builds a complete Finite Element Model(FEM) with a parametric loading and boundary conditions. It models the engine and wing mounts and it associates to the FEM a stress model with all inputs necessary to support the strength analysis and sizing process. Therefore, it is possible to perform optimization on the shape or topology because the full chain from geometry/topology update to sizing with weight calculation is automated.[25] Actually, modifying the pylon geometry, wing loads are impacted and have to be updated. To be accurate in our conclusions and not to miss some key effects, an update of these loads is required. A high-fidelity modeling of the wing, with the use of CFD models, is not really relevant for the structure optimization. Instead we found a compromise in using the $MSC^{®}$ Nastran aeroelastic solutions (SOL 144, 145, 146) based on doublet lattice method (DLM). They provide a good solution to compute manoeuver, flutter and gust load cases. Here, flutter are not taken into account as a pylon load case but as an optimization constraint.

Figure 19 presents the pylon modelling process based on PARMOS/FEMIX.

PRESTO[24] is used for the rapid sizing of the pylon composite structure; it delivers an optimized catalogue selection for trade-offs and optimum thickness/area distributions for sizing within this catalogue selection (see Figure 20). And thanks to catalogues it can also deliver a detailed definition of elements including profile details and stacking sequences (see Figure 21). The choice of catalogues allows to perform trade-offs regarding for example the material, the profile type and even some stress margin policy. It also gives a weight indicator (weight of the optimized finite elements) and the updated finite element model.

To account for stiffness-driven criteria (like flutter constraint) a gradient-based optimization is achieved by a bi-level structure optimization process by coupling PRESTO with Nastran SOL200.

2. Use-case assumptions

The aim of this study is the optimization of an engine pylon in case of an aircraft re-engine. It means we consider the engine as an input parameter and not a design variable for the optimization. In addition, the pylon concept regarding the engine integration is an invariant of the study and the type of engine and wing interfaces will remain the same. Due to a large shape modification, these fixed concepts could be not relevant

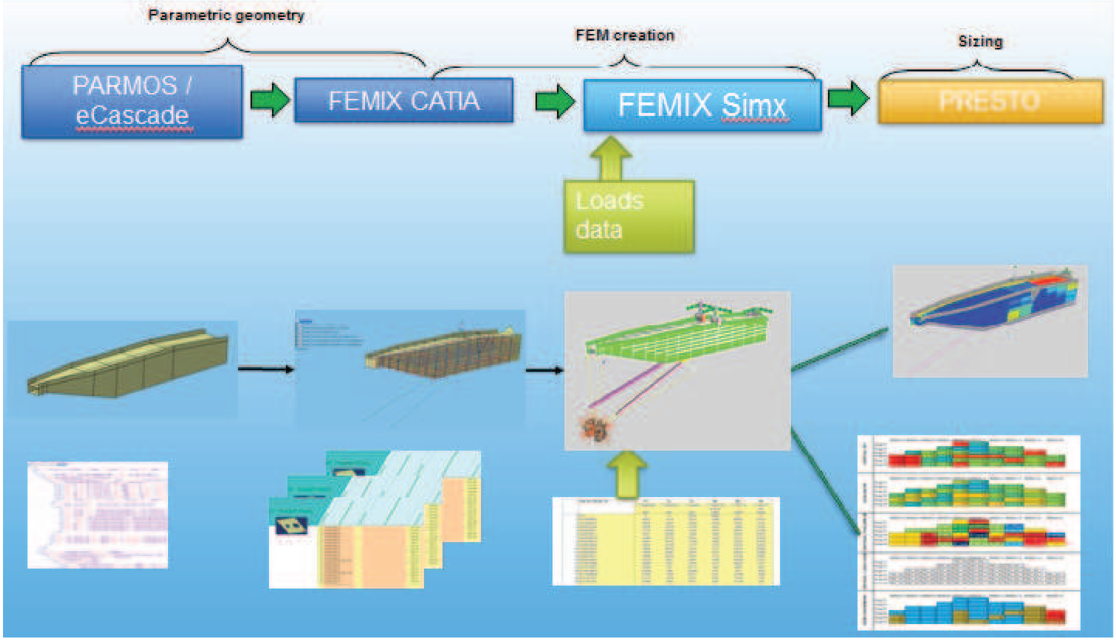


Figure 19: Pylon modelling process based on PARMOS/FEMIX

to reach the optimum. In this case a manual preparation of template could be required. Finally, in the first stage of this project, loads of the pylon are frozen. This assumption will be removed in a second step.

3. Structural parametrization

The complete description of the pylon's primary structure needs several hundreds of parameters. For a relative quick MDO process, managing as many variables, just for one discipline is not really possible. So, only 10 parameters are exposed to the MDO level and shared with other disciplines. The others parameters are private and are only managed by the discipline itself (linked to the shared parameters or set with a default value).The choice on taking into account the exposed parameters as design variables is given to the user. In order to model a large scope of pylon geometries, the following parameters are finally chosen as possible shared design variables:

- X and Z engine positions
- 2 rib heights
- 6 rib widths (3 widths on each spar panels)

In order to validate the robustness of the structural workflow, a Design of Experiment (DoE) has been performed for ΔX, ΔZ variations of the engine X and Z position. Figure 22 shows the structural geometries for two points of the DoE: in green $\Delta X = +300$ mm, $\Delta Z = 0$ mm and in blue $\Delta X = -300$ mm, $\Delta Z = -250$ mm. Figures 23a and 23b present the finite element models corresponding to these two structural geometries.

VII. Conclusion and Future work

The MDA-MDO project contributes to the development of an industrial MDO capability on three key aspects : a MDO platform, MDO formulations and methodologies, and a demonstrator pylon optimization test case. A platform architecture has been proposed and tested to address industrial MDO design problems. This architecture is specifically designed to take advantage of existing disciplinary optimization capabilities in the industry. The platform enables an easy interfacing with different workflow engines, in which disciplinary optimization suites are integrated. The core component of the platform is a Generic Engine for MDO

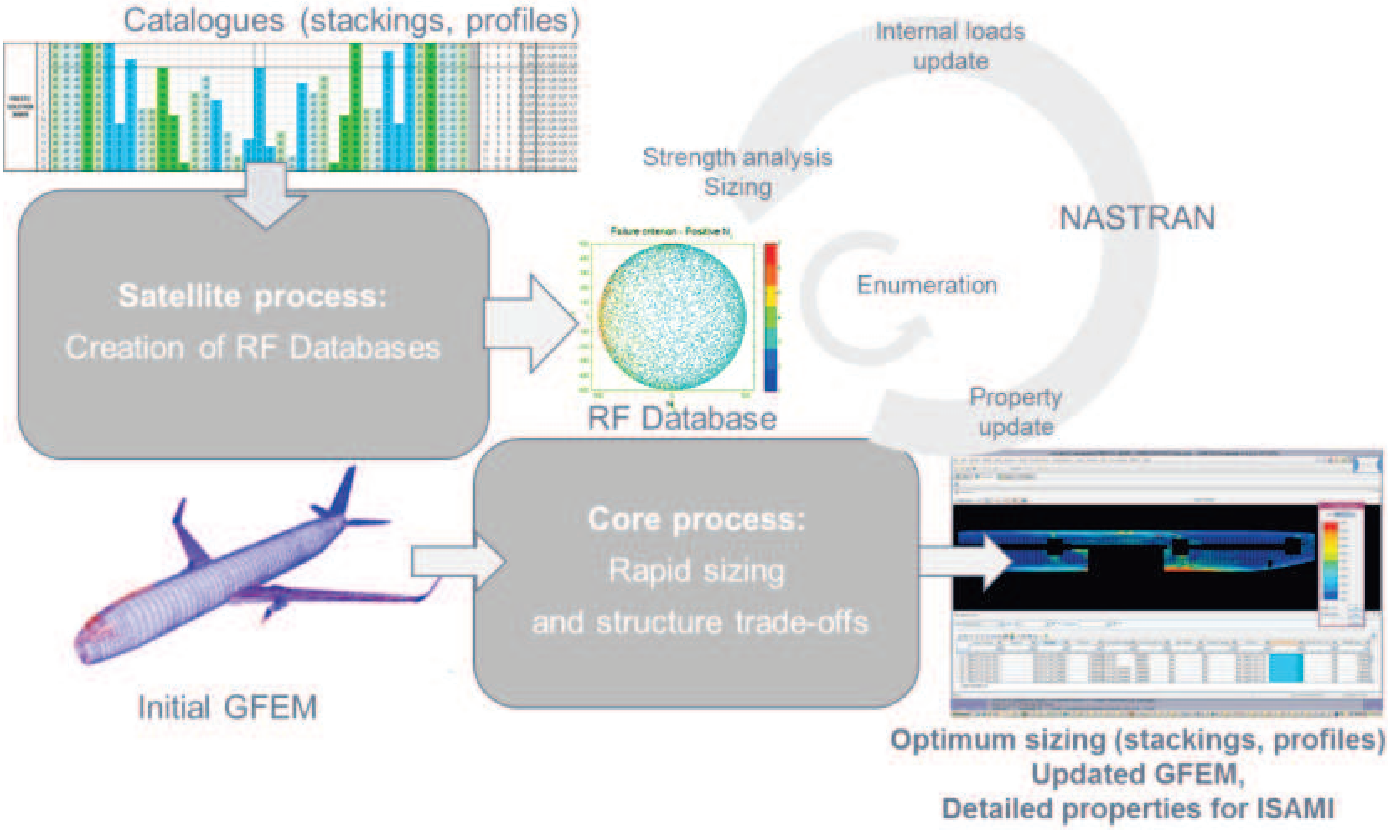
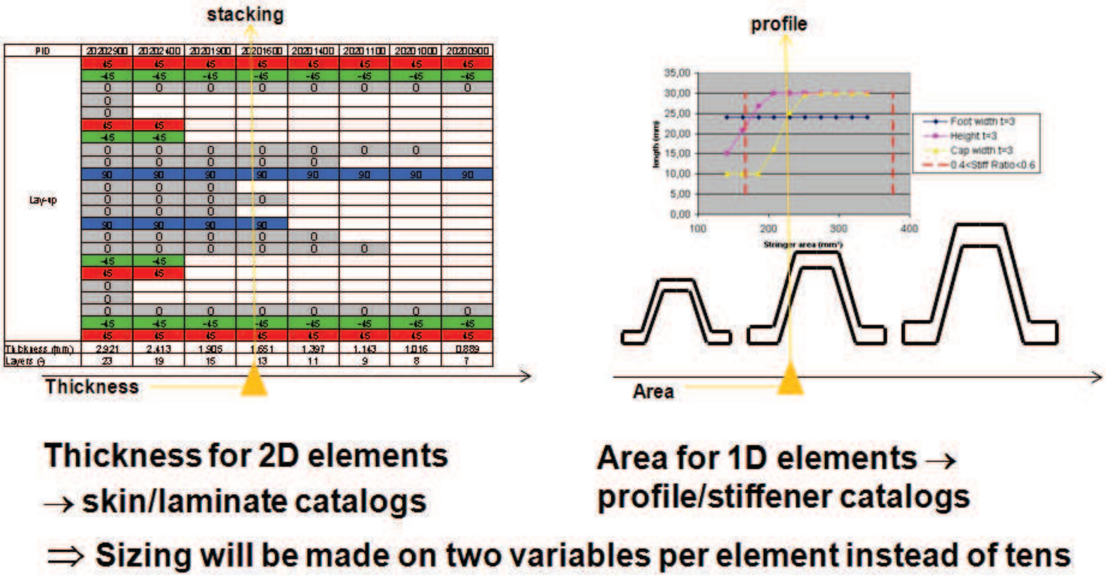


Figure 20: PRESTO: a bi-step rapid sizing process built on a database approach.



PID	20202900	20202400	20201900	20201600	20201400	20201100	20201000	20200900
Lay-up	45	45	45	45	45	45	45	45
	-45	-45	-45	-45	-45	-45	-45	-45
	0	0	0	0	0	0	0	0
	0							
	0							
	45	45						
	-45	-45						
	0	0	0	0	0	0	0	
	0	0	0	0	0			
	90	90	90	90	90	90	90	90
	0	0	0					
	0	0	0	0				
	0	0	0					
	90	90	90	90				
	0	0	0	0	0			
	0	0	0	0	0	0		
	-45	-45						
	45	45						
	0							
	0							
	0	0	0	0	0	0	0	0
	-45	-45	-45	-45	-45	-45	-45	-45
	45	45	45	45	45	45	45	45
Thickness (mm)	2.921	2.413	1.905	1.651	1.397	1.143	1.016	0.889
Layers (-)	23	19	15	13	11	9	8	7

Thickness for 2D elements → skin/laminate catalogs

Area for 1D elements → profile/stiffener catalogs

⇒ Sizing will be made on two variables per element instead of tens

Figure 21: PRESTO principle of catalogues.

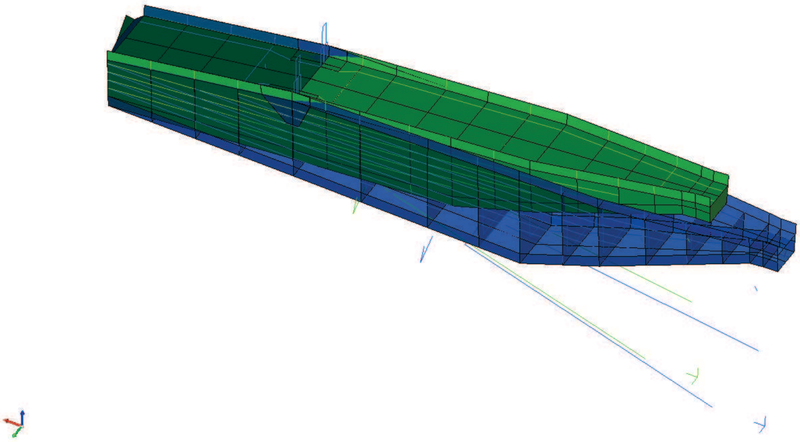


Figure 22: Structural geometries: in green $\Delta X = +300$ mm, $\Delta Z = 0$ mm; in blue $\Delta X = -300$ mm, $\Delta Z = -250$ mm

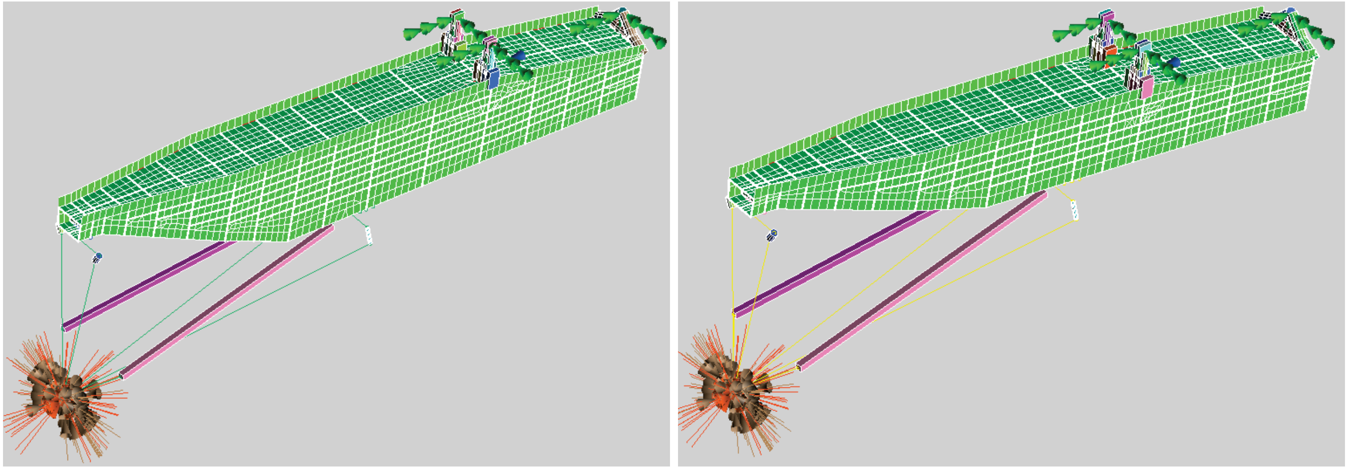


Figure 23: Finite Element Model for $\Delta X = +300$ mm, $\Delta Z = 0$ mm (left) and for $\Delta X = -300$ mm, $\Delta Z = -250$ mm (right)

scenarios (GEMS), independent of the disciplinary tools, that orchestrates the execution of the processes based on MDO formulations. A new family of MDO formulations is proposed for the project test case, derived from the BLISS formulation. The classical SSBJ MDO test case is first used to validate the platform concept, and the target family of MDO formulations. Finally, a multi-fidelity pylon aero-structural optimization test case is under realization. The parametric aerodynamic and structural models have been created. The final aim of the application, under progress, is to assess the impact of a new engine on the global aircraft performances.

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References

[1] Martins, J.R.R.A. and Lambe Andrew B. "Multidisciplinary Design Optimization: A Survey of Architectures." In *AIAA Journal, 51*, 2013.

[2] Kroo, I., et al. "Multidisciplinary optimization methods for aircraft preliminary design." In *AIAA paper 4325*, 1994.

[3] Braun, R.D., Kroo, I. and A.A. Moore. "Use of the collaborative optimization architecture for launch vehicle design." In *Proceedings of the 6th AIAA/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, 1996.

[4] Defoort, S. et al. "Multidisciplinary Aerospace System Design: Principles, Issues and Onera Experience." In *AerospaceLab 4*, 2012

[5] Blondeau, C. et al. "A Bi-Level High Fidelity Aero-Structural Integrated Design Methodology - A Focus on the Structural Sizing Process". In *RAeS 3rd Aircraft Structural Design Conference*, 2012

[6] Anderson, R.F., "Determination of the Characteristics of Tapered Wings", In *NACA report*, 1936

[7] Raymer, D.P., "Aircraft Design: A Conceptual Approach (Education Series)", In *AIAA*, 2006

[8] Niu, C., "Airframe structural design: practical design information and data on aircraft structures" In *Conmilit Press*, 1988

[9] Powell, M. JD., "A direct search optimization method that models the objective and constraint functions by linear interpolation.", In *Advances in optimization and numerical analysis. Springer Netherlands*, 1994.

[10] Kraft, D. "A software package for sequential quadratic programming." In *Forschungsbericht- Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt*, 1988.

[11] Lambe, A.B. and Martins, J.R.R.A., "Extension to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes.", In *Structural and Multidisciplinary Optimization*, 2012

[12] Gray, J. and Moore, K.T. and Naylor, B.A. "OpenMDAO: An open source framework for multidisciplinary analysis and optimization." In *AIAA/ISSMO Multidisciplinary Analysis Optimization Conference Proceedings. Vol. 5*, 2010.

[13] Gazaix, A., Gendre, P. et al. "Investigation of Multi-Disciplinary Optimisation for Aircraft Preliminary Design." In *SAE Technical Paper*, 2011.

[14] Martins, J.R.R.A. and Marriage, C.. "An object-oriented framework for multidisciplinary design optimization." In *3rd AIAA multidisciplinary design optimization specialist conference. Waikiki, Hawaii, USA*, 2007.

[15] Sobieszczanski-Sobieski, J. and Agte, J.S. and Sandusky, R.R. Jr. "Bi-level integrated system synthesis (BLISS)." In *Technical Report TM-1998-208715, NASA, Langley Research Center*, 1998.

[16] Gallard, F. "Aircraft shape optimization for mission performance." PhD thesis, INP Toulouse, 2014.

[17] Meaux, M. and Cormery, M. and and Voizard, G. "Viscous aerodynamic shape optimization based on the discrete adjoint state for 3d industrial configurations." In *4th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Jyväskylä, Finland, July*, 2004.

[18] Scilab. "Scilab: Free and Open Source software for numerical computation." Scilab Enterprises, 2012

[19] Eclipse, I. D. E. "Eclipse Foundation.", 2007.

[20] Tabaste, O and Borrelli, P.P. and Gazaix, A. and Badier, Y. "Aircraft thermal architecture trade off management use case". In *NAFEMS World Congress 2015 inc. the 2nd International SPDM Conference — San Diego, CA*, 2015

[21] Gallard, F. and Mohammadi, B. and Montagnac, M. and Meaux, M. "An adaptive multipoint formulation for robust parametric optimization". In *Journal of Optimization Theory and Applications*, 2015

[22] Cambier, L. and Heib, S. and Plot, S. "The Onera elsA CFD software: input from research and feedback from industry". In *Mechanics and Industry*, 2013

[23] Balzano, M. and Sarouille, P. "Use of SimXpert in the Context of the Colossus FEMIX Project". *Key Note presentation, MSC Virtual Product Development Conference*, 2009

[24] Grihon, S. and Malherbe, G. "A rapid sizing tool for airframe conceptual design studies". *LMS European Aeronautical Conference, Toulouse*, 2012

[25] Grihon, S. and Carpentier, A. "Rapid Sizing end-to-end process for Airbus Airframe Design". *Siemens PLM Software European Aerospace Engineering Conference*, 2015

[26] Lafage, R. "XDSMJs library". https://github.com/OneraHub/XDSMjs