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# Design and Integrated Verification of Hybrid-Electric Power System for Regional Aircraft †

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**Abstract**

The design of Hybrid-Electric Regional (HER) aircraft represents a great challenge due to the systems' complexity and their level of integration and results in a great expense of resources. To overcome these issues, the Open Digital Environment for Hybrid-Electric Regional Architecture (ODE4HERA) project is developing an Open Digital Platform (ODP) to accelerate the design process. The platform is validated using a pilot case which focuses on powertrain systems and covers the entire development process, from requirements definition to Virtual Integrated Verification and Validation (IV&V). At first, the design is performed using state-of-the-art tools; then it is repeated using preliminary ODP modules to evaluate the achieved benefits.

**Keywords:** digital continuity; integrated virtual verification and validation; model based design; model based system engineering; multidisciplinary design analysis and optimization

## 1. Introduction

As aeronautical systems become more advanced, the complexity of the design process greatly increases making the development of competitive solutions more difficult and time/cost demanding. This is especially true for Hybrid-Electric Regional (HER) vehicles since their powertrains can handle over twice the number of parameters and many times more combinations than conventional configurations [1].

The Open Digital Environment for Hybrid-Electric Regional Architecture (ODE4HERA) project aims to accelerate the design process through the development of an Open Digital Platform (ODP) that combines Model Based System Engineering (MBSE), Multidisciplinary Design Analysis and Optimization (MDAO), Simulation Data Management (SDM), and Product Lifecycle Management (PLM) technologies, extending them with novel open interfaces and data transformation technologies. At the end of the project, the platform is



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expected to achieve a Technology Readiness Level (TRL) of 5 [1]. The approach of the ODP is different from other known frameworks, such as RCE or OpenMDAO.

The Remote Component Environment (RCE), developed by DLR, provides a peer-to-peer workflow execution framework widely used in aerospace projects such as AGILE and AGILE 4.0 [2]. Similarly, OpenMDAO is a NASA Python-based framework optimized for multidisciplinary design optimization [3]. Both tools excel at workflow execution; however, they operate as point-to-point integration platforms requiring manual tool interface definition and offer limited support for requirements traceability. The ODP from ODE4HERA distinguishes itself by adopting SysMLv2 as a vendor-neutral, semantically rich data model that enables automatic data transformation between heterogeneous tools with minimal user intervention, while simultaneously integrating MBSE with MDAO—a capability not provided by existing workflow integration frameworks [4–7].

This paper presents the activities carried out in the context of Work Package 4 aiming to validate the ODP through a pilot case, the so-called Application Case 1. This focuses on the powertrain of Ultra Efficient Regional Aircraft [8], shown in Figure 1.

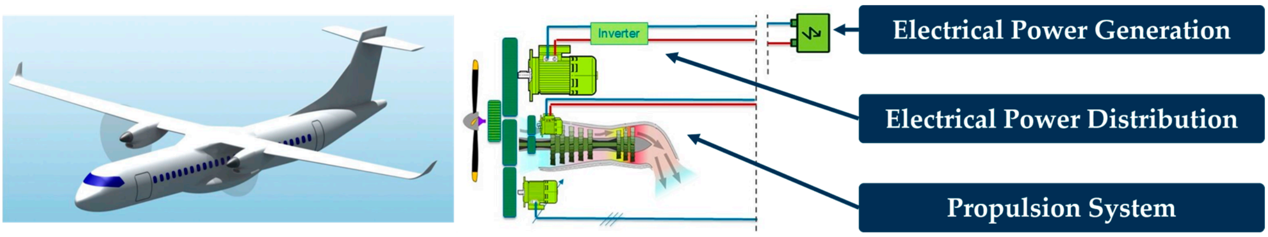


**Figure 1.** Application Case 1 design problem and scope [8].

The analyzed System of Interest (SoI) contains the following Aircraft Systems:

- Electrical Power Generation, consisting of two battery packs;
- Electrical Power Distribution, providing electrical power to propulsive and non-propulsive loads. The Smart Electric Power Management manages the electrical generation and load shedding/optimization in all flight conditions;
- Propulsive System, containing thermal engines and electric motors arranged in a parallel layout. They transmit the movement to the propeller through a gearbox.

## 2. Development Process

The design process followed in Application Case 1 is summarized in Figure 2 together with the adopted tools.

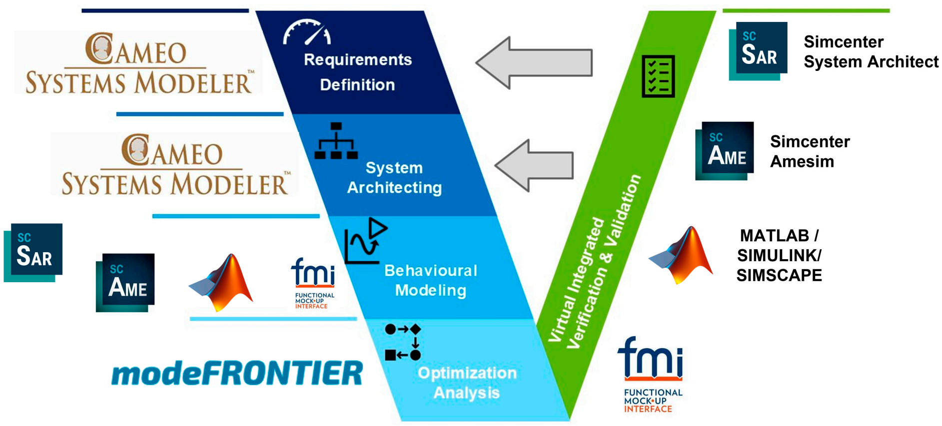


**Figure 2.** Application Case 1 design process. The integrated verification and validation accelerate the development of the models, bringing the right side of the V closer to the left side.

### 2.1. Definition of Requirements and Functional Modeling

According to the MagicGrid approach [9], the starting point is the collection of Top Level Aircraft Requirements (TLARs) in Cameo Systems Modeler™ [10], an MBSE environment allowing generation, analysis and management of SysML-compliant models. TLARs represent what stakeholders expect from the SoI and define, among the others, the maximum payload or the design range demanded by the stakeholders. They are decomposed at lower levels following the process described in [9], that is articulated in:

- Operational Analysis which considers the SoI as a Black-Box to understand how it interacts with the environment. As a result, Vehicle Requirements are obtained to define how the entire vehicle will meet the TLARs (e.g., the Vehicle Requirement "the Aircraft shall generate the adequate thrust for its on-ground and in-flight maneuvers" fulfills the TLARs about the design mission profile).
- Functional Analysis, that considers the SoI as a White-Box to detail how it operates. As a result, Vehicle Requirements are decomposed into Aircraft Systems Requirements. For instance, the Vehicle Requirement presented earlier results in several specifications for the Aircraft Systems, such as "the Electrical Power Generation shall provide the requested amount of electric power to actuate the Propulsion System".

At the end, starting from about 20 TLARs, near 60 Vehicle Requirements and 330 Aircraft Systems Requirements are obtained.

### 2.2. System Architecture

Figure 3 reports the System Architecture defined in Cameo Systems Modeler™ 19.0 through Internal Block Diagrams. The SoI is decomposed into multiple levels:

- Level 1 corresponds to the vehicle and models the interfaces exchanged among the Aircraft Systems;
- Each Level 2 block represents a single Aircraft System (e.g., Propulsion System);
- Level 3 is associated with components. For example, Propulsion System includes electric motors, thermal engines, gearboxes, and propellers.

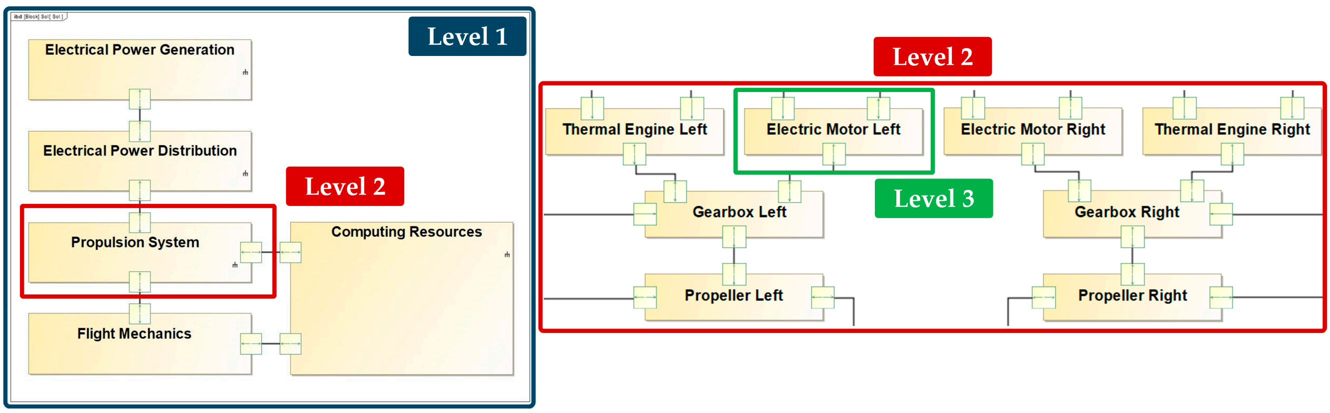


**Figure 3.** System Architecture with three levels of granularity in Cameo Systems Modeler™.

### 2.3. Behavioral Modeling

Simcenter™ System Architect 2410 [11], an environment for creation of heterogeneous system simulation architectures, is adopted to define the behavioral model since it allows to integrate models from a dissimilar toolchain in the most possible agnostic way. As shown in Figure 4, the global model is composed of:

- Flight Mechanics, a point mass model described by Nonlinear Aircraft Performance Equations in MATLAB®/Simulink® R2024b and based on a custom aerodynamic database. This part is widely described in the companion paper [12].
- Electrical Power Generation and Distribution is realized in Simscape™ R2023b, while the Smart Electric Power Management in MATLAB®/Simulink® R2023b. The latter implements the hybridization function adjusting the torque reference of the electric motor based on the different flight phase.
- Propulsion System in Simcenter™ Amesim™ 2310 [13], a systems simulation platform to virtually assess systems performance. Effects of both thermal engine and electric motor are modeled.

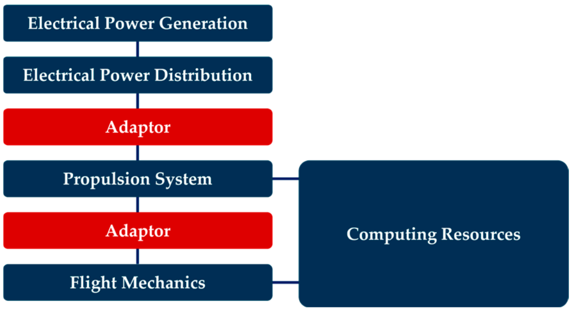


**Figure 4.** Structure of the behavioral model. The adaptors in the red box are interfaces between the different FMUs.

Aerodynamic and Propulsion System models are provided by the Hybrid-Electric Regional Architecture (HERA) consortium [14] through a Cooperation Agreement and cannot be disclosed. Flight Mechanics and Electrical Power Generation and Distribution are exported as Functional Mock-up Units (FMUs) [15] to be integrated in Simcenter™ System Architect, whereas a direct integration can be performed for the Propulsion System. During the integration, custom-made interfaces with the Propulsion System (called adaptors in Figure 4) are introduced. In fact, Simcenter™ Amesim™ uses ports with multiple input and output signals, where each port could be of different nature (e.g., mechanical). Hence, it is not possible to simply demux the signals, and the adaptors become necessary.

### *2.4. Optimization Analysis*

modeFRONTIER® 2025R2 [16], a tool allowing to integrate behavioral models and performing MDAO, is adopted. In order to highlight possible critical steps, an incremental approach is followed for MDAO. Starting from several architectures summarized in Table 1, the All-At-Once was selected as a first step because it represents a conservative benchmark for evaluating the performance of the modeFRONTIER® adaptor, resulting in a more straightforward implementation of the Multi-Disciplinary Analysis (MDA), i.e., the part of MDAO architecture focused on handling residuals.

**Table 1.** MDAO architectures features.

| Architecture | Optimizer Variables | Consistency (Feasibility) | MDA Execution |
|---|---|---|---|
| All-At-Once | Design + State + Coupling Variables | Guaranteed only at convergence | No separate MDA; Residuals are handled as optimization constraints |
| Individual Discipline Feasible | Design + Coupling Variables | Guaranteed only at convergence | Disciplines evaluated in parallel; Consistency enforced via constraints |
| Multi-Disciplinary Feasible | Only Design Variables | Guaranteed at every iteration | Full MDA loop each optimization step |

Thus, a single macromodel in Simcenter™ Amesim™ describing the entire SoI is integrated in modeFRONTIER® to speed up the analysis due to its reduced computational time. The identified inputs, objectives, and constraints are listed in Table 2. The decision to try minimizing Maximum Take-Off Weight (MTOW) is due to the fact that, compared to a conventional configuration, a hybrid powertrain greatly increases the mass of the vehicle [17]. As a first step, linear relationships are considered between:

**Table 2.** MDAO inputs, objectives and constraints.

| Inputs | Objectives | Constraints |
|---|---|---|
| • $P_{EM}$<br>• $Q_{battery}$<br>• $m_{fuel}$ | • Min. MTOW<br>• Min fuel burnt, $CO_2$ and $NO_X$ | • The vehicle shall complete the mission with predetermined air speed, altitude and propeller velocity.<br>• $m_{fuel}$ and the State of Charge of the batteries at the end of the mission shall have safety values. |

- The mass of the electric motor ($m_{EM}$) and its power ($P_{EM}$);
- The mass of the battery ($m_{battery}$) and its capacity ($Q_{battery}$).

As MTOW changes with $m_{EM}$ and $m_{battery}$, values of wing reference surface $S_{ref}$ are updated:

$$S_{ref} = \frac{\text{MTOW}}{\text{MTOW}_0} \cdot S_{ref_0} \tag{1}$$

with $\text{MTOW}_0$ and $S_{ref_0}$ referred to the baseline configuration. In this way, the "snowball effect" could be taken into account: the larger the aircraft weight, the bigger the structure will be—as well as the $S_{ref}$—and thus the higher the fuel burnt, which in turn further increases the weight [18]. The optimized configuration is determined with a trade-off between minimum of MTOW and fuel burnt.

### *2.5. Integrated Virtual Verification and Validation*

The ODP actively supports the Virtual Integrated Verification and Validation (IV&V) process: compared to the traditional V cycle, where Verification and Validation activities start at a later stage, in Virtual IV&V they begin during the definition/design phase. In fact, models are continuously integrated, thus allowing Model-in-the-Loop verification from the beginning of the design phase. As a result, many errors are anticipated with respect to the traditional V-cycle. This, together with the higher efficiency of the ODP, brings to a reduction in lead time and increase in cost effectiveness [1].

## 3. Open Digital Platform

Even though at the end of the project ODP will combine MBSE, MDO, PLM, and SDM technologies, at this stage only the MDO module has a maturity level that allows for the evaluation of its benefits.

### *3.1. modeFRONTIER® Adaptor*

The MDAO module relies on a modeFRONTIER® adaptor, i.e., a Python 3.12 script that converts input data from SysML v2 files into new ready-to-use files by modeFRONTIER® thus generating the optimization workflow. Figure 5 outlines the main steps to follow:

1. The inputs are represented by two SysML v2 files. The first one is generated by the MDAx tool and stores input and output variables, constraints, objective functions, etc. MDAx is a framework from DLR to formulate MDAO workflows by automatically matching tool inputs to outputs [5].
2. The second SysML v2 file contains lower and upper bounds and thresholds of constraints.
3. Then the modeFRONTIER® adaptor, implemented in Python, can be run to generate text and .json files, and to automatically open the workflow template.
4. Inputs, outputs, constraints, objectives, and design variables domains are automatically imported from the .json file. If performed manually, this task is time-consuming and could easily introduce errors, especially when there is a large number of input/output nodes or design variables domains. In contrast, the adaptor abruptly reduces this effort and the risk of mistakes.
5. The user loads the workflow from an off-the-shelf repository and selects the optimization algorithm. After that, some manual integrations into the automatically generated workflow are needed (e.g., for comparing the target curves with the computed ones to verify the constraints).
6. Once the run has ended, the user selects the best solution and exports it to a .des file. Then, the second part of the adaptor (called writer) updates the original SysMLv2 file to exchange the updated values with the rest of the ODP.

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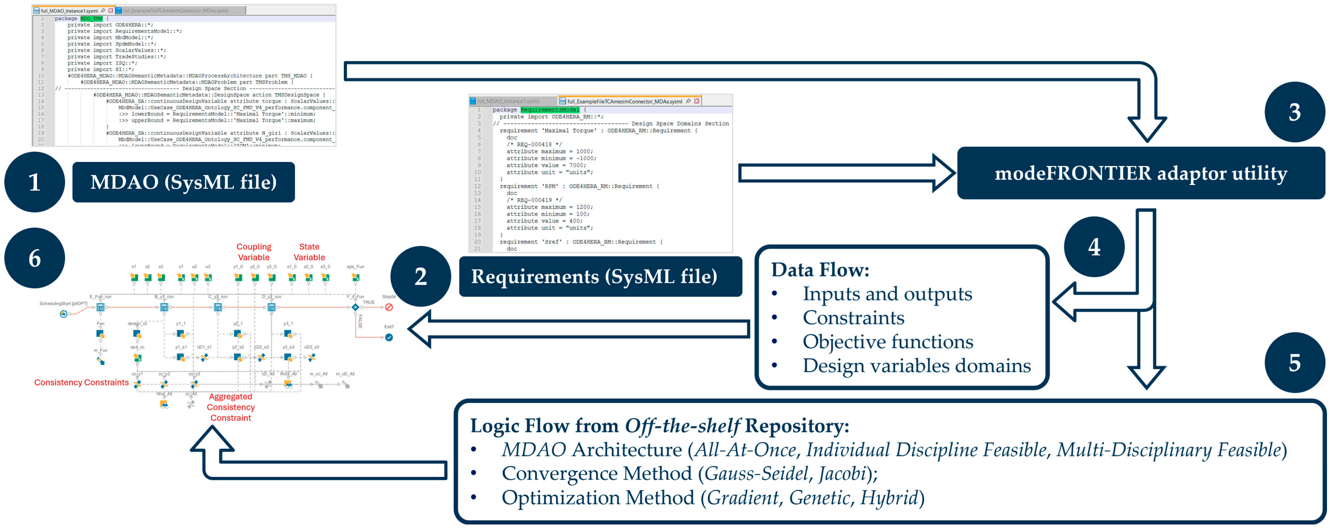


**Figure 5.** MDAO supported by modeFRONTIER® adaptor.

### 3.2. Assessment of modeFRONTIER® Adaptor Capabilities

In order to effectively assess the capabilities of the modeFRONTIER® adaptor, additional variables with respect to those from Table 2 are considered. In detail, the assessment is performed with 27 design variables and 41 outputs. Additional inputs are kept constant during the optimization, and the other outputs are not involved in any objective. Then "integration" is selected as a suitable metric to evaluate the MDAO module. In detail, it refers to the process of combining multiple applications or systems to function as a unified whole [19]. In the context of ODP, integration is the ability to seamlessly combine different models (functional, logical, and behavioral) and exchange data across various phases of the product lifecycle involving different tools, domains, and disciplines. This metric can be evaluated using the "Time required for integrating existing tools, models, and data" as the indicator. A procedure based on the "Task Time Estimation via Decomposition" approach is adopted to break down complex activity into smaller tasks, as shown in Table 3.

**Table 3.** Assessment of modeFRONTIER® adaptor capabilities based on integration time.

| Task | Manual Procedure (h) | modeFRONTIER® Adaptor (h) | Notes |
|---|---|---|---|
| Data collection | 1 | 0 (from SysMLv2 files) | |
| Selection of MDAO architecture | 0.25 | 0 (from SysMLv2 files) | |
| Insertion of input/output nodes with name assignment | 2 * | 0 (from SysMLv2 files) | Checks are required for manual procedure |
| Assignment of domains/steps for input variables | 0.5 * | 0 (from SysMLv2 files) | |
| Insertion of objective functions and constraints | 0.25 * | 0 (from SysMLv2 files) | |
| Initial debugging | 1 | 0.5 | Fewer errors |
| Functionality testing | 1 | 0.5 | Faster if the model is correct |
| Total time | 6 | 1 | Time saving: 83% |

* Proportional to input/output data amount.

It is evident that the adaptor reduces the manual actions for users, as well as the manual errors. Moreover, the analyzed case is conservative: the optimization workflow is based on one integrated discipline and the All-At-Once architecture is simple to implement manually because it does not require the direct management of coupling between disciplines. Furthermore, the human labor needed for some tasks is proportional to the amount of data flow entities. However, in this case, the number is not large in the context of aeronautic design and the resulting estimation can again be considered conservative.

Since most of the ODP modules are currently under development, only a qualitative analysis of the impacts of modeFRONTIER® adaptor on IV&V phase could be provided:

- The traceability and automation of repetitive tasks reduce the manual errors thus accelerating the Virtual IV&V process. Even errors due to misinterpretation of inputs from previous phases are minimized thanks to the usage of SysML v2 files defined automatically by other ODP modules.
- Some requirements could be automatically implemented as constraints in MDAO using the modeFRONTIER® adaptor thus making their testing unnecessary.

## 4. Conclusions and Outlook

At first, the entire design cycle is executed using state-of-the-art tools to estimate the efforts needed to develop HER configurations with standard industrial practices and the desired capabilities of the platform. Then, by analyzing the modeFRONTIER® adaptor, it has emerged that the ODP could significantly increase efficiency thanks to the automatization of manual time-consuming tasks and to the traceability among the tools.

In the future, the approach adopted to study the MDAO module could be extended to the entire ODP to evaluate its benefits across the entire design process. Moreover, the SoI will be extended by including other Aircraft Systems and more complex models. Regarding the modeFRONTIER® adaptor, new functionalities are being implemented (e.g., the automation of the result writing function and management of the entire Pareto Curve) and other MDAO architectures will be tested.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| FMU | Functional Mock-Up Unit |
| HER | Hybrid-Electric Regional |
| HERA | Hybrid-Electric Regional Architecture |
| IV&V | Integrated Verification and Validation |
| MBSE | Model Based System Engineering |
| MDA | Multi-Disciplinary Analysis |
| MDAO | Multi-Disciplinary Analysis Optimization |
| MTOW | Maximum Take-Off Weight |
| ODE4HERA | Open Digital Environment for Hybrid-Electric Regional Architecture |
| ODP | Open Digital Platform |
| PLM | Product Lifecycle Management |
| RCE | Remote Component Environment |
| SDM | Simulation Data Management |
| SoI | System of Interest |
| TLAR | Top Level Aircraft Requirement |
| TRL | Technology Readiness Level |

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