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A MBSE-based framework for aircraft systems design and evaluation

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Abstract

A raising number of flights has increased the impact of aviation on the environment. To mitigate these impacts, the Clean Sky 2 initiative has set goals for the aviation industry to reduce fuel consumption, CO2 emissions and perceived noise for the next generation of commercial aircraft. In addition, Clean Sky 2 aims to be a key contributor to accelerate the progress toward the Flightpath 2050 goals set by the Advisory Council for Aeronautics Research for net-zero emissions. As a consequence, there is a huge effort on the development of new greener technologies for aircraft systems. The overall design and integration of an aerospace system today encompasses a varying range of engineering disciplines and models at different levels of abstraction and complexity. The collaborative project Modelling and Simulation tools for Systems Integration on Aircraft (MISSION), developed under the European Union Clean Sky 2 Program, aims to develop and demonstrate an integrated modelling, simulation, design and optimization framework for aircraft systems and subsystems leveraging Model Based System Engineering principles to the aerospace industry. This paper proposes a Model Based System Engineering-based modelling framework supporting the whole aerospace product design workflow from requirements definition to system certification. Several advanced analyses were developed within this framework and can be applied at any stage of the design workflow. This framework enables an optimized aircraft systems design quantified against aircraft key performance indicators. As a case study, we demonstrate the capabilities of the proposed framework to support the design of a modular hybrid electric platform and evaluate its impact at aircraft level.

1. Introduction

Air passenger traffic is increasing every year. As a result some considerations need to be taken to meet the market needs but also to reduce the envioronmental impact of aircraft. Therefore, the Advisory Council for Aeronautics Research (ACARE) set goals for the aviation industry to achieve net-zero CO2 emissions by 2050. In this context, the European Commission initiated the Clean Sky 2 Technology [10] to provide funding for projects supporting the aviation industry to meet those goals which are more ambitious than those of the initial Clean Sky program. The work presented in this paper is part of Modelling and Simulation tools for Systems Integration on Aircraft (MISSION) project [16] [2] funded by Clean Sky 2. The scope of the MISSION project is the develpment towards a seamless integrated and interconnected framework supporting aircraft design and development. MISSION project has ended and the content of this paper represents the main output of the project consisting on a methodological approach to support the whole aerospace product design from requirements defintion, system modelling to system verification. Specifically, this paper focuses on the use of Model Based System Engineering (MBSE) approaches and techniques towards a modular and flexible framework. The methods presented allow designers to build models with reusable components librairies enabling the integration and interaction between different aircraft systems.
This paper is structured as follows: Section 2 presents an overview of the previous work done in the field of aircraft system design process. Section 3 describes the proposed framework developed in the MISSION project and the section of it that we focus this paper on. Section 4 illustrates the demonstration of the framework to design a modular thermal platform extended to a hybrid electric platform. Finally Section 5 summarises the conclusions and discusses future work.

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2. State-of-the-Art

Although the efficiency of aircraft systems is increasing, the emissions from aviation are outpacing the efficiency gains. This means that any effort towards a faster and more integrated design and verification process for aircraft systems can only serve to accelerate the improvements on aircraft design in order to reduce emissions. Therefore, several others projects are proposed to improve aircraft design in order to reduce emissions. For example, within the Horizon 2020 framework, the goal of GLOWOPT (Global-Warming-Optimized Aircraft Design) project [7], is to develop and validate Climate Coast Functions (CCFs) to minimize global warming and their application to the multidisciplinary design optimization of next-generation aircraft. Another Horizon project is AGILE [5] [6] where the target was to accelerate the development of complex aeronautical systems using advanced multidisplinary optimization techniques based on MBSE approach.
CATS (Climate Compatible Air Transport System) project [12], carried out by DLR, proposed a simulation and analysis approach to provide an assessment of operational and technological options to reduce the climate impact of air traffic. Another internal project of DLR is WeCare (Utilizing Weather Information for Climate Efficient and Eco Efficient Future Aviation) project [13] where the objective was to reduce the climate impact using measurements and modelling approaches to understand the the atmospheric impact from aviation.
Others projects were proposed to improve the aircraft design and validation. For example, ACROSS [3], MOET [8], VIVACE [9] projects proposed frameworks for the design, development and integration of different aircraft systems. In [18], the authors presented a MBSE framework using Object Process Methodology to design an aircraft with dynamic landing constraints. The use case consists on the design of a civil transport aircraft to transport cargo from origin to destination during landing phase. A framework combining MDAO (Multidisciplinary Design Analysis and Optimization), MBSE and MBSA (Model-Based Safety Assessment) is proposed in [15] to optimally design an aircraft while meeting all the safety requirements by using a surveillance UAV as a use case. This combination enables the integration of the different discplines involved in the design of an aircraft and also the treacability of the initial requirements with elements of the systems.

3. Model Based System Engineering based framework

As illustrated in Figure 1, The MBSE-based framework discussed in this paper includes several steps to enable an agile and modular aircraft systems design.

1. Requirements definition: the first step in the proposed process involves the identification of requirements.

2. Architecture models: the defined requirements are then used to model the logical system architecture and define components properties like interface stereotypes. SysML language [19] is used for modelling the architectures. Introducing the architectural layer as the step between the products definition (requirements) and its design (domain specific models) is indicated and common practice for complex systems like aircraft or their subsystems.

3. System models: After the SysML model has been designed with attention to the physical properties, it is automatically transformed to a Modelica representation [1] to be filled with models of representative physical behaviour by a domain expert. This step ensures the architecture of the system and the physical connection between sybsytems are maintained as defined and agreed during system architecture definition.

4. Test models: the last step consists of evaluating the system using virtual testing methods (Model in the loop, software in the loop, hardware in the loop, etc.) considering the defined requirements.

5. Central data management: a central data management system is a key element to ensure a seamless integration. It closes the gap between data silos from different development tasks by creating the link between workflow artefacts generated in the model based development process. This is necessary to achieve full traceability and to enable worflow automation as well as advanced tracking and analysis capabilities.

6. Advanced analysis: several advanced analysis were developped and can be applied at any stage of the framework. As examples we can mention:

    - Architecture exploration: This technique is based on the method originally developped at Raytheon Technologies Research Center [23]. It involves a search and formal reasonning procedure that navigates through the design space in order to find configuration that do not violate design requirements (also referred to as "constraints"). The adapted method follows a multi-level filtering process where the design space is adaptively reduces in successive refinement levels.

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- Model Order Reduction (MOR): As part of the framework and in order to improve the integartion of complex systems with other systems in the aircraft, a MOR technique was developed. The technique represents a key technological enabler for model simplification by reducing the model complexity while keeping the prediction accuracy and for integration with more complex simulation environments.
- Uncertainty Quantification (UQ): while MOR reduces the complexity of the system, increased computational efficiency of the reduced model comes at the cost of accuracy and introduces uncertainty within the models. Therefore, a UQ technique was developed within the framework in order to quantify the uncertainty in these models to be able to fully understand the accuracy of the results.

The goal of the proposed framework was to enable model exchange across tools, domains and discplines based on open standards, ensure traceability and consistency of models across discplines and an early stage aerospace systems validation and verification. In this paper, we will not focus on the advanced anaylsis but rather on the integration of the architecture and system models.

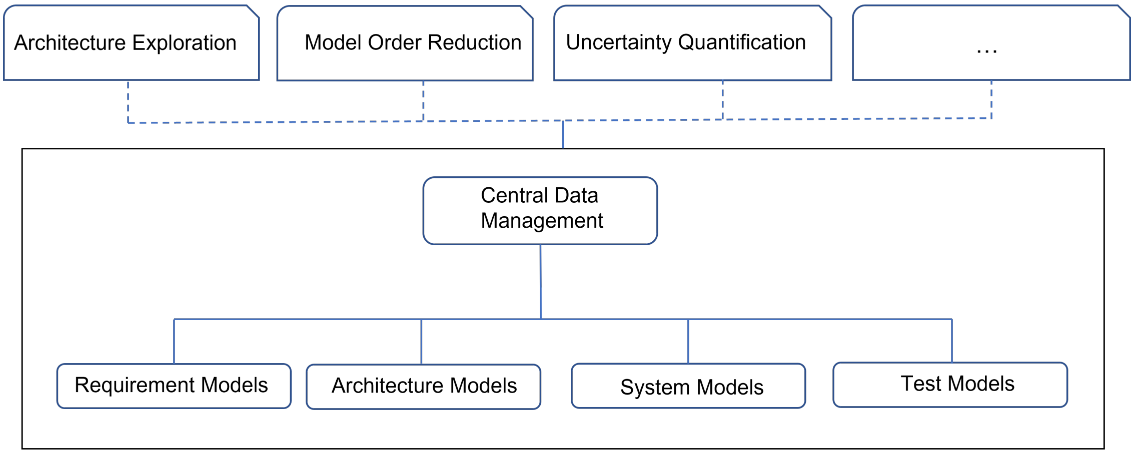

Figure 1: MBSE-based framework for aircraft systems design

4. Case Study

The scope of this work is the development towards a seamless integrated, more connected workflow demonstrating more efficient processes with faster results and less rework time in todays highly collaborative aerospace domain design application. With a model based integration approach, along the whole process from requirements definition to the verified system, it will become possible to integrate aircraft and system level aspects and interactions typical for such development. The development towards more electric aircraft is an ongoing effort in the aviation industry, therefore, we will demonstrate our framework to design a modular thermal platform that is extended to a hybrid electric platform. The hybrid electric use case was not originally considered in the scope of this work, but the framework is flexible enough to accelerate going from electric aircraft systems to more electric propulsion.

4.1 Thermal Platform

4.1.1 Thermal Platform Architecture

The thermal platform architecture considered in this paper is a conventional architecture from a single aisle commercial aircraft. In this architecture, the Environmental Control System (ECS) provides the conditioned air for the cabin, cockpit, cargo and avionics bay and the other main thermal loads are dissipated by the cooling loops for the engines and the electrical generators. Following the framework described above, the architecture of the thermal platfom is formalized in a SysML model that can be read by other tools in the framework to enable faster integration and testing.
The decomposition of the systems considered for the thermal platform is formalized in a SysML Block Definition Diagram (BDD) as shown in Figure 2. Each of the blocks in the BDD represent an aircraft system involved in thermal load transfer during the aircraft mission. Some of these systems also play a significant role in the power platform; these blocks are marked in green in the figure.
The integration of the power and thermal layers in the aircraft level assessment requires these system models to be

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simulated considering their dual role and introduces computing complexity when running the analysis. In order to perform the analysis at aircraft level each of the blocks in the BDD correspond to a set of system models that include modules to calculate different aspects of the system performance and size, such as weight, volume, dynamic response etc. These models range from very simple historic regression models, to first-order physics steady state models used in early conceptual design, to more complex physics-based dynamic models of the system performance. They can be simulated together in order to analyse their performance and how their interaction affects each other and their relative sizing and weight. As seen in Figure 2, there are many systems involved in the analysis of the aircraft system architecture performance.
Since the purpose of this paper is to demonstrate the integration of the thermal and power layers and the analysis of thermal system performance at aircraft level, a few key systems were selected for more detailed analysis and simulation. Details of the integration use case will be presented in the next section.

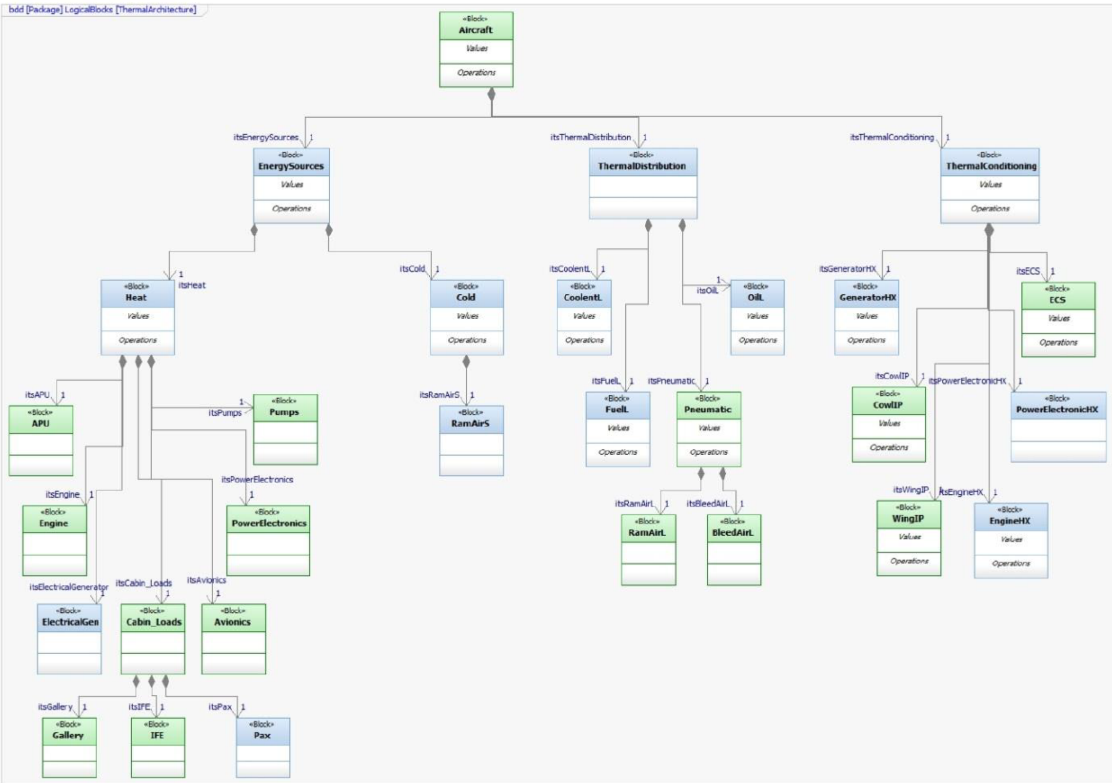

Figure 2: SysML block definition diagram for the thermal platform architecture

4.1.2 Thermal Layer Integration

The main purpose of this use case is to demonstrate the integration and interactions between different aircraft systems and their impact on performance at aircraft level. Therefore, for the purposes of this paper we choose to: capture the effect of the integration of the engine, the ECS and the electric system generator on each of their performances and the overall impact of the integration on the aircraft mission performance.
The physics-based dynamic model of the ECS system, included in the use case, has been developed under another CleanSky2 project in the Systems ITD called Adaptive Environmental Control System (aECS) [4]. The goal of the aECS project is not only to model a traditional ECS but also design a new configuration for the ECS that reduces the fresh air flow while maintaining cabin air quality and therefore reducing the impact of the ECS on the overall aircraft operation. The overall energy saving is achieved by the reduction of the fresh air and integration of air quality sensors and filtration systems together with an enhanced control strategy that is able to maintain the desired level of cabin air quality.
This is a good example of sub-systems interaction in which performances of the individual sub-systems are mutually influenced and the overall system has a sizable impact on the aircraft. This use case is also of particular interest because it demonstrates the interaction between different system models developed by different teams and for different

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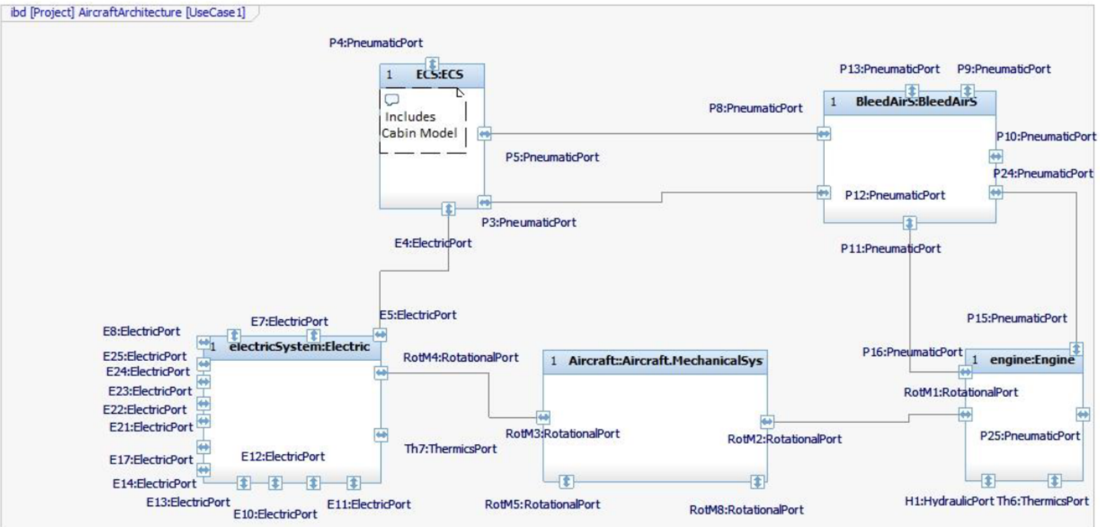

Figure 3: ECS, electrical system and engine integration use case

purposes and dealing with different physical domains. For example, the engine system was developped by combustion experts, the electric system was developed by electrical engineers and the ECS system came from a different project. In addition, each of these systems is at least repeated once more in the aircraft in a symmetrical way for a twin-engine aircraft, meaning that the dynamic simulation can be reused to capture not just the integration of one set of components but both in order to capture their full impact at aircraft level when operating in a twin engine configuration.
The ECS provides conditionned air to the cabin crew and passengers, and is the most energy demanding sub-system in an aircraft, being responsible for up to 5% of the fuel consumption of the engines during cruise. This energy consumption is mostly due to the compressed air the ECS requires in order to condition the air in the aircraft cockpit and cabin. In the case of a pneumatic ECS, which is the most common type, bleed air is extracted directly from the engines after a compression phase. Moreover, some electric power is required by the ECS, for example to power the air distribution system or the recirculation fan. The power transmission into the generator is a transformation from mechanical to electrical in the form of the generator being driven via a gearbox from the engine shaft. It is thus evident that the engine, ECS and electric generator systems are coupled and there is a dependency between the performances of the different systems.
A high-level schematic of the sub-systems interconnection is illustrated in the SysML IBD diagram shown in Figure 3. The original objective of the engine model was to build a physics-based simulation model of a typical gas turbine engine (specifically a turbofan) in a modular way to ease the integration with other aircraft system models. The use case presented illustrates the integration of a key thermal layer componenet (ECS) with key power layer components such as the engine. However the use case has been designed in a flexible and modular way such that other systems can be integrated dynamically. Therefore, an extension of this use case is possible, combining the engine and generator cooling loops system with the existing integrated models considered in the original use case. This will allow us to incorporate a more complex thermal system that will require additional considerations for thermal management and architecture design.The SysML IBD of the extension of the use case is shown in Figure 5 and Figure 6 illustrates the proposed structure of thermal oil loop with the engine and the generator. As shown in Figure 6, the left part of the diagram is the oil cooling loop for engine while the right loop is the electrical generator cooling. The FCOC is decoupled into two FCOC with one for each thermal loop. Apart from the FCOC and the related fuel pump, each oil loop includes an oil pump, one ACOC and a heat source (engine/generator). The integration between the heat source and the thermal oil loop will be that of the heat transfer through the heat flow connection. Basically, oil absorbs heat when circulating through heat source and afterwards flows through the heat exchangers to dissipate heat to the heat sinks (fuel, air). Then, the pressurized and cooled oil will be circulated back to the heat source again.

The integration enables the designer to carry out technology trade-off studies on new technologies and to utilize the framework and its tools to demonstrate Model Based Systems Engineering (MBSE) based methods in modelling and design activities [21]. SimulationX [14] has been selected as the main environment to perform the integration and co-simulation of the selected sybsystems in alignment with the rest of the tools used in the MISSION project. Through the use of the workflow described in the previous section, the use case sysML IBD can be automatically converted into

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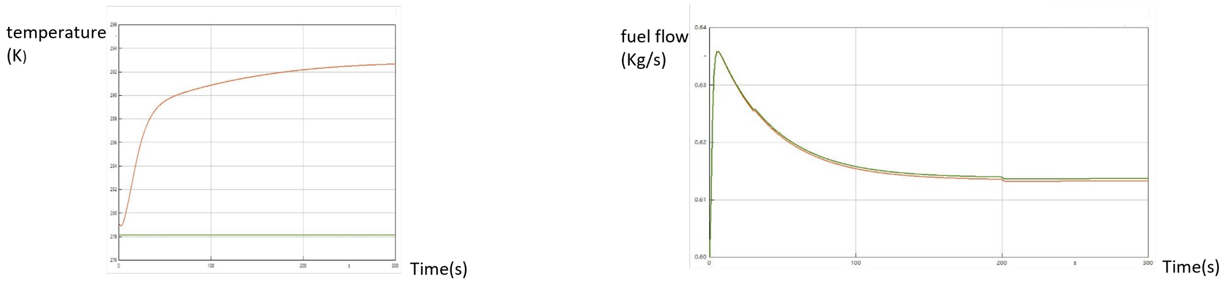
a Modelica skeleton in Simulation X providing the necessary structure for populating each of the empty blocks with the corresponding system models.
The use case presented is especially interesting from an integration standpoint because each of the system models involved is modelled by a different team using a different approach. For example, while the engine model is directly developed in SimulationX, the aECS model was developed in Dymola [20] and imported into SimulationX via FMU [11]. The Functional Mockup Interface (FMI) is a model-exchange and co-simulation standard used in MISSION toolchain for the communication across tools. The import via FMU enables the aECS team to protect important intellectual property within the model and the integration across tools. It also adds an extra layer of complexity as the FMU I/O is based on unidirectional signals without specified units. This means that direct physical connections in Modelica cannot be used, and therefore a predefined integration approach was followed, whereby the interfaces are fixed a priori including the format of the signal and measurement unit and if changes are needed both modelling teams collaborate to iteratively change them at the same time.
The system level integration is not the only relevant analysis of the use case, the integration and analyses of the different systems at aircraft level has been carried out using steady state models for each system and mission point with the primary objective to capture changes in aircraft design weight and performance throughout the whole mission profile of an aircraft.
Figure 4 shows the simulation result of the thermal oil loop integration with the focus on the fuel control of the integration system. Two aspects has been analysed: the impact of the fuel temperature on the engine combustor efficiency and the need of an active control of the fuel flow to be able to maintain the desired thrust produced by the engine and correct the fuel flow needed based on the combustor efficiency. In the simulation results, the impact on the fuel flow demand can be appreciated due to the introduction of a fuel flow controller which is used to request the correct amount of fuel flow to be injected into the combustor to allow the engine to maintain the desired thrust. This controller is accounting for all the external conditions that have an impact on the ability of the engine to produce thrust including the variation of fuel flow characteristics such as temperature.



Fuel flow temperature before entering the combustor:
fixed at 5C (green) by the controller, fuel flow temperature equal to output flow temperature (red), not controlled.

Fuel flow to maintain desired thrust:
with fuel flow temperature at fixed 5 C (green) and at variable fuel flow temperature from FCOC output temperature (red).

Figure 4: Thermal oil lool integration simulation

In this paper, we provide the demonstration of the integration of the thermal and power layers in the aircraft level platform. This integration demonstration is presented for a use case involving multiple systems (electrical system, environmental control system, etc.) that have significant electrical power and thermal flows between them. The demonstration has showed that the design and modelling platform successfully incorporated interactions between these primary aircraft systems and their impact on performance at aircraft level. The MBSE-based framework was used to build models with reusable components libraries and to demonstrate hierarchical modelling with ability to choose different sub-components and structures, expose different results and parameters for further design tasks.

4.2 Hybrid Platfrom

One of the key objective of this work is to demonstrate the flexibility of the framework to different use cases with different systems and different physics at different fidelities. When MISSION as a project was originally conceived the prevalence of hybrid electric propulsion options for aviation research was not as present. However as the project progresses we realized that the the use case components described in the previous section have all the building blocks of a parallel hybrid electric configuration. Hybrid electric propulsion systems are attracting more attentions to achieve the net-zero goal as they bring the benefits of reduced fuel consumptionm noise and emissions. In a parallel hybrid

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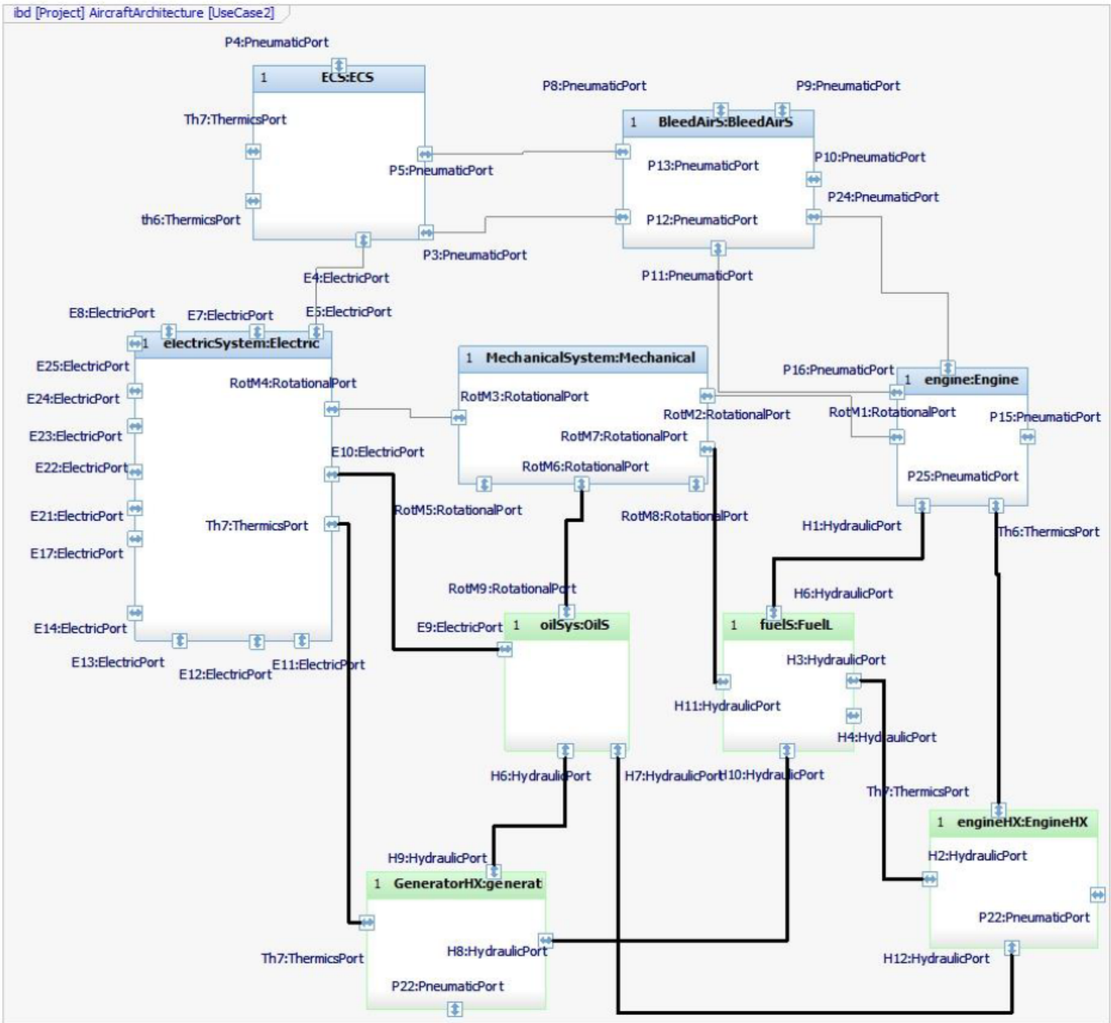

Figure 5: Extension of the use case with engine amd generator cooling loops

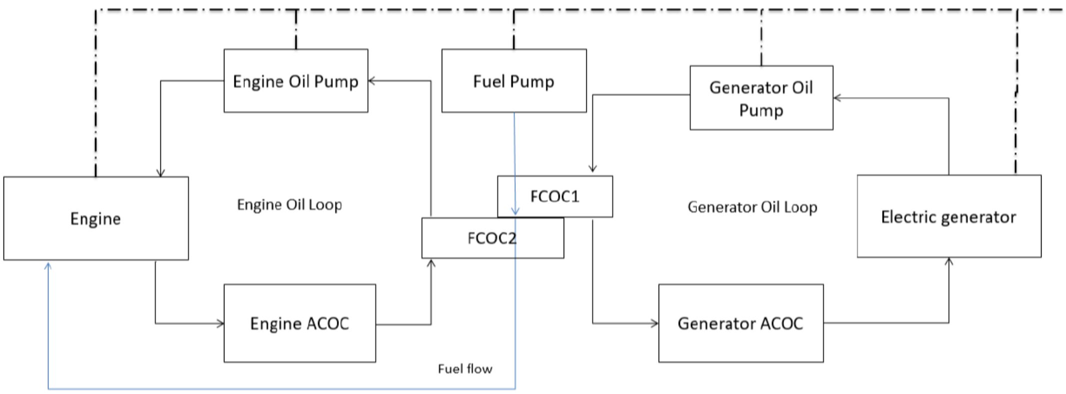

Figure 6: Proposed structure of thermal oil loop integration with Engine/Generator

propulsion system, the engine and the electric motor are combined to improve the performance of the system. They are connected mechanically so they can contribute to the system energy either simultaneously or individually [22].

As illustrated in Figure 8, the thermal use case was extended into a hybrid use case by adding a motor generator

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to the existing configuration. The same MBSE based workflow is followed by designing the system architecture in SysML and then transform it to Modelica language. Figure 7 shows the extension of the electric system including the motor generator. The engine is then integrated with the motor generator to allow a bidirectional power transfer and includes an output of the thermal losses that is emulated based on power flow and its direction. We have used the model of a Pratt Whitney GTF engine [17] to reflect current trends in aerospace propulsion. The Geared Turbofan has the advantage of having different speeds in the fan spool and the low speed compressor spool which allows for higher flexibility in the engine accesory gearbox to power secondary systems. The new simplified electric system is very fast and can be integrated with the long simulation scale for the engine and thermal models.
Once the integration is complete and the ability of the engine to include input mechanical power is verified, the use case can be improved by including a more detailed electrical model for the motor generator that while still respecting the same interfaces given by the SyML architecture, it better represents the physics of the electrical system. Therefore, the electrical system is expanded and the new model is based on a detailed synchronous motor model including a torque controller and a thermal output from the thermal power loss. Simulation of the new platform shows that the complexity of the model coupled with the fast dynamics characteristic of the new electrical system makes the model a lot slower in integration. We solved this integration challenge by integrating the electrical system as an FMU with a separate solver and ensuring both solver settings were optimized for computational speed while ensuring synchronization and the right level of fidelity in the model outputs, thus improving simulation time. Figure 9 illustrates the generation of a FMU from the hybrid use case with the new electrical model. This integrated model for the hybrid use case including the FMU for the new electrical system was then simulated for a classic hybrid electric assist scenario. The scenario chosen was the electric motor adding power to the low pressure spool of the engine during the last phase of climbing to cruise altitudes and then the electric system drawing power form the engine during cruise to replenish the batteries. The power levels chosen to illustrate this case were 1000hp added to the engine at the beginning of the hybrid boost, reducing to 900hp as the boost continues, and then extracting 90hp for a lengh of time during cruise. These power levels are illustrative of one possible hybrid assist scenario and vary depending on how much added power the parallel hybrid architecture adds to the engine. Figure 10 shows the integration results from modelling this scenario for the integrated cooling system for the engine and electrical system. These results serve as an example of the kind of physics simulated in this use case and the different analysis permitted through the approach presented in the paper. The flexibility and modularity of approach, allowed us to model new architectures and use all the tools given by the MISSION platform modelling and integration approach to merge models coming from different teams and work to improve the simulation results.

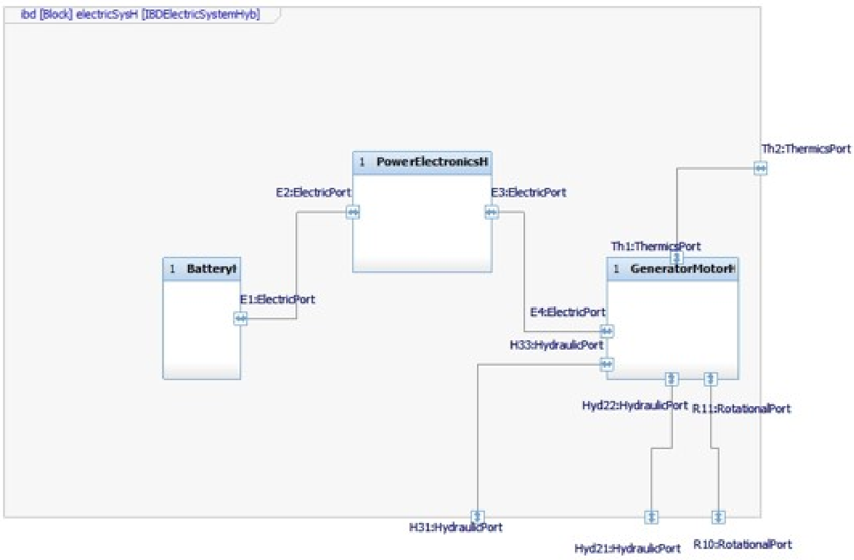

Figure 7: Extension of the electrical system

5. Conclusion

In this paper, we proposed a seamless integrated framework from requirements definition up to the virtual system verification for aerospace domain. The framework is coupled with innovative analysis techniques leveraged to explore,

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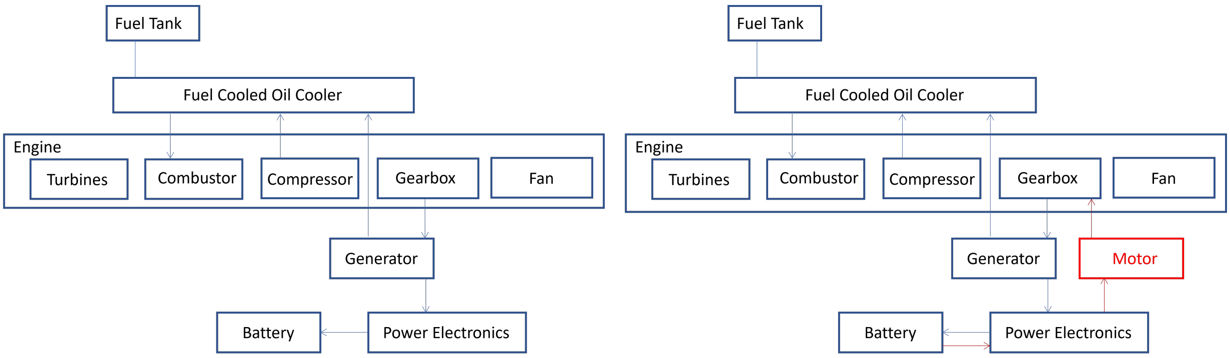


(a) Thermal configuration (b) Hybrid electric configuration

Figure 8: Extension of the exisitng thermal platform to a hybrid electric platform

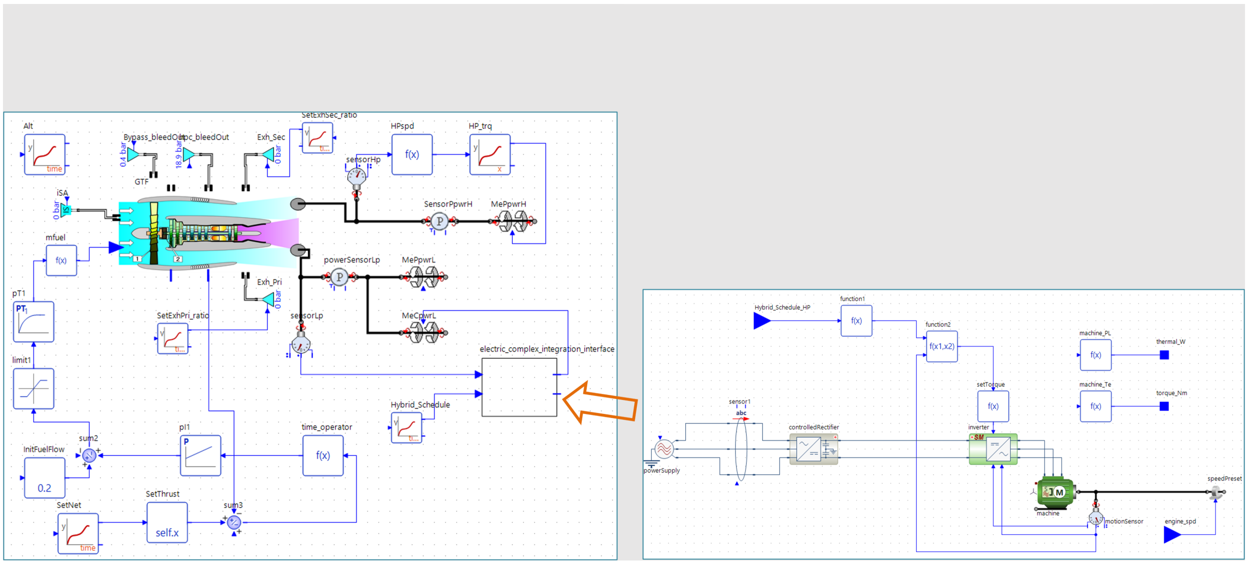
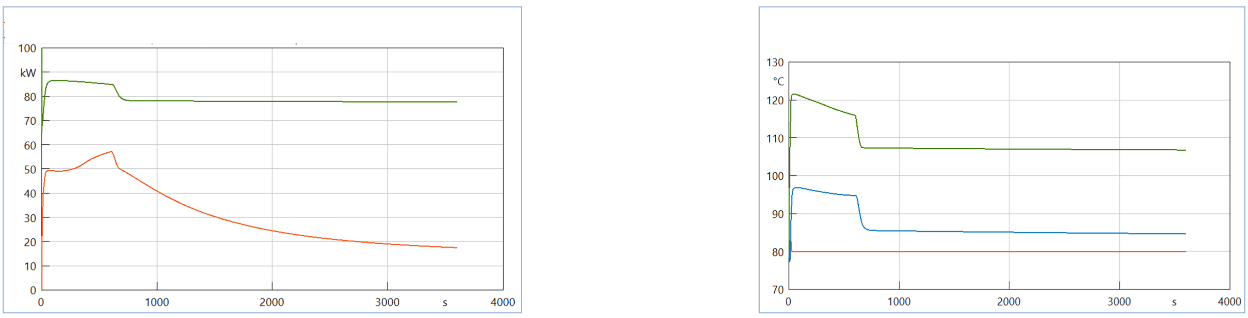


Figure 9: FMU generated from the hybrid use case with complex electrical model



Heat flow rate (kW): heat flow across heat exchangers for the hybrid use case FCOC (red), ACOC (green)

Oil temperature (C): Temperature of the oil after cooling engine spool (green) and after ACOC (blue) and FCOC (red), FCOC is the last step of the process and returns oil to base temperature of 80C

Figure 10: Simulation of the hybrid use case integration with the electrical model FMU

design and integrate aircraft systems to evaluate its impact from systems on aircraft and vice versa. The flexibility and modularity were key factors as the framework can include many dynamic models of many different systems coming from different teams. Those models were created using different approaches and different modeling tools. The modu-

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larity enables the replacement of any of the systems with a more or less complex model as needed while respecting the interfaces given by the formalized architecture using SysML language.

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