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Accelerating the Development of Complex Systems in Aeronautics via MBSE and MDAO: a Roadmap to Agility

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The ever-increasing complexity of systems under development in aerospace is demanding to streamline and accelerate the development of innovative products, across the diverse disciplines, and throughout the entire life-cycle. The European funded research and innovation AGILE project introduced a novel paradigm to Multidisciplinary Design Analysis and Optimization (MDAO) processes, shortening the setup time of MDAO systems to more than 40%, with respect to conventional MDAO approaches. However, AGILE project scope was limited to the design and the optimization of the aircraft product itself, for a given set of design requirements and for a given architecture. The follow-up European funded project AGILE4.0 expands the scope, including also the upstream systems engineering phases of the development life-cycle, within the trade-off and optimization activities. This work introduces the conceptual framework under development, which leverages digital engineering approaches and in particular Model Based Systems Engineering (MBSE). The focus of the framework is on accelerating the setup, deployment and operation of MBSE systems, as well as on streamlining the integration with MDAO system, to in turn accelerate the development of aircraft products. The focus of the framework is on the bridge between MDAO and MBSE. The paper also introduces the on-going investigations which make use of the framework and are collaboratively performed by the Consortium consisting of 18 International Organizations.

Nomenclature

AGILE	=	Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
AF	=	Architectural Framework
DE	=	Digital Engineering
MBSE	=	Model Based Systems Engineering
MD(A)O	=	Multidisciplinary Design (Analysis) Optimization
OAD	=	Overall Aircraft Design
PDP	=	Product Development Process
PIDO	=	Process Integration and Design Optimization
SE	=	Systems Engineering
SoI	=	System of Interest
SoS	=	System of Systems
SOTA	=	State Of The Art
XDSM	=	eXtended Design Structure Matrix

I. Introduction

A major challenge in the transport sector is to make economic growth compatible with sustainability and environmental constraints, while remaining competitive and innovative. The development of innovative complex systems involves highly multidisciplinary processes with requirements and constraints on the system itself (e.g. an aircraft), on the individual components and technologies to be integrated (e.g. disruptive propulsion), and on the interactions with the external environment and other systems involved (e.g. multi-modal transportation system). However, major factors are hampering the cost and time effective developments of novel aeronautical products. At first, the complexity of innovative systems under development in aerospace is increasing due to the higher functionalities demand to meet ambitious goals, and expected longer life in-service in evolving, and sometimes uncertain, operational conditions. Furthermore, the outsourcing trend and the globalization nature of the aeronautical industry, needs to connect all the people, skills and technologies

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involved in collaborative, multi-national and cross organizational processes, into seamless operations, across the diverse disciplines, and throughout the entire life-cycle of the product.

Therefore, there is the need to **streamline and accelerate the development of innovative systems**, across the diverse disciplines, the domains involved, and throughout the entire life-cycle of the development.

Digital Engineering (DE) initiatives are targeting, among others, to leverage a modeling-based approaches (in place of document-based approaches) of every information produces and/or consumed by all the stakeholders involved in the development. Such a digital transformation requires a novel design paradigm to enable a fast and efficient integration of multidisciplinary models, accounting for design, manufacturing and certification domains. In particular, Model Based Systems Engineering (MBSE) approaches and technologies, are identified as the key technology to enable the development of innovative systems in any field. Aerospace, automotive and defense organizations have already recognized the added value of Model-Based Systems Engineering (MBSE) in streamlining the design, development, deployment and verification of complex products. The increasing interest on MBSE is promoted by all the potential advantages that an innovative model-based approach would have over a traditional document-based approach. Advantages brought by MBSE approached include increased traceability between the whole information developed and handled during the development process, improved communications and clarity among designers and stakeholders, automatic validation and verification activities (reducing the design cycles iterations), and re-use of data and results in multiple follow-up projects (formalization of knowledge).

A key feature, to overcome the challenges for the development of novel aerospace systems, is the ability to take the right decisions in complex scenario, and to make it fast than ever before. Nevertheless, identifying, generating, and assessing novel design solutions is a multidisciplinary effort requiring an agility which today is not in place yet.

Therefore, the next generation of development methodologies, will need to leverage digital design engineering principles to seamlessly connect technologies, skills, and people involved in collaborative, multi-national and cross-organizational development processes, by means of a digital representations of production systems and supply chains, and by seamless operating across the diverse disciplines, and throughout the entire life-cycle of the product. Multidisciplinary Design Analysis Optimization (MDAO) [1], offers the support to perform complex decision making. However, the authors have previously identified that major obstacles in the current generation of ***MDAO systems*** are largely related to the efforts required to setup complex collaborative frameworks. Ciampa et al. quantified that 60 to 80% of the project time may be necessary to setup such a process [2] [3]. The AGILE project [4] funded by the European Commission and recently ended in 2018 has developed a novel approach, called ***AGILE Paradigm***, in order to streamline the setup, deployment and operations of collaborative *MDAO systems* [5]. The *AGILE Paradigm*, has introduced a shift of focus, with at its core the acceleration of the deployment and the operation of *MDAO systems*, which in turns can be effectively exploited to accelerate the development of complex products (e.g. novel aircraft). The technologies developed to implement such approach, have been demonstrated for multiple collaborative aircraft design and optimization applications, shortening the setup time to more than 40%, with respect to conventional MDAO approaches [6]. However, AGILE project scope was limited to the design and the optimization of the aircraft design itself, for a given set of design requirements and for a given architecture of the aircraft.

The newly launched European Commission funded project AGILE4.0 (2019-2022) [7], aims to include in the development process also for architectural trade-off, and requirements engineering, and to streamline the connection of those typical upstream systems engineering (or MBSE) phases to MDAO, leveraging digital engineering.

The work presented in this paper introduce the principles and the overall approach at the foundation of the framework under development in the AGILE4.0 project. The focus of the paper is on the integration of MBSE and MDAO principles, for the development of complex aeronautical products. The paper introduces the concept of *development system* at first. Thereafter, it introduces the AGILE4.0 project. Thereafter, the MBSE and MDAO connection is described, as well as an overview on the development framework. Finally, a number of application cases from the AGILE4.0 project, are introduced, with focus on challenges and trade-off to be addressed.

II. Towards Agility for the Development of Complex System

Aerospace systems (such as aircraft, spacecraft, and satellites) have always been characterized by advancing technologies in response to changing needs, shift of expectations, disruptions in the markets and the technology landscape. This trend includes the continuous development of novel design methods and emerging approaches, in "support" of the development of "better" products. Therefore, to design the next generation of aerospace "***system of interest***" (SoI), it is always necessary to develop along the next generation of supporting "***development systems***". The relationship between *design system* and *complex system under development* is shown in Figure 1. In the current aerospace technology landscape, the next generation of *design systems,* need to leverage digital design engineering approaches in order to accelerate the development time, minimizing associated costs, and at the same time maximizing value of the products under developments.

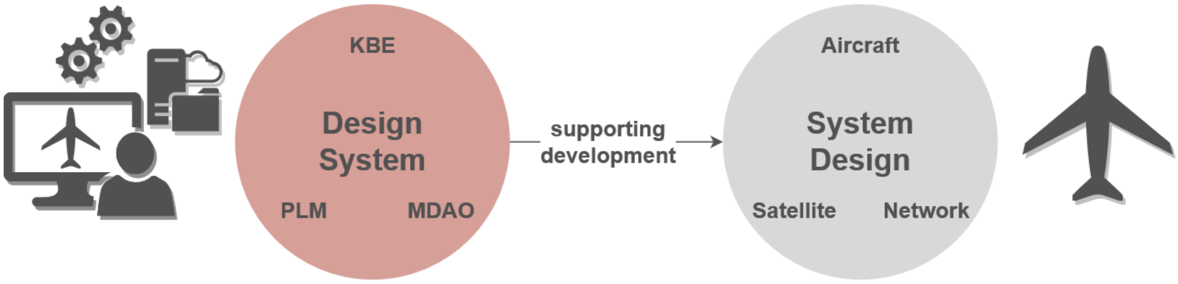

Figure 1 The development of the next generation of complex systems (e.g. the novel aircraft concepts), needs to be supported by the next generation of "design systems". MDAO systems are a specialized category of the design systems.

A multitude of *design systems* are potentially available today in aircraft development programs. These, include PLM (Product Life Management) integrated environment, MDAO (Multidisciplinary Design Analysis Optimization) frameworks, KBE (Knowledge Based Engineering) applications, collaborative management platforms, MBSE (Model Based Systems Engineering) environments, often operating in parallel. However, despite decades of investments in R&D activities, most of them are not exploited in the development of line's products yet. As products to be engineered grows in functionalities and capabilities, such *design systems* grow in complexity as well, resulting in a "lack of agility" to be effectively deployed. In turns, the management of the complexity of the design system becomes the key challenge, to manage the complexity of the system under development.

MDAO systems are a specific category of *design systems* which, despite the known advantages, are not yet fully exploited outside of the research programs. It has to be noted that for "*design system*", the authors do not identify the single software solution or application, but the entire eco-system of technologies and services which are needed to perform a design and optimization task. Therefore, a *MDAO system* comprises elements such as: disciplinary simulation tools, process integration design optimization (PIDO) environments, optimization frameworks, communication channels, data exchange spaces, computational infrastructure, as well as expertise and know-how of the engaged development team.

Recently, ***MBSE systems***, have also became the target of larger investments. A *MBSE system* comprises elements such as: definition of stakeholders and requirements management, architecture generation and evaluation, life-cycle modeling, and resource planning platforms.

The authors have previously identified in Ref. [6] that major obstacles are largely related to the efforts required to setup and deploy large-scale MDAO collaborative design processes, more than resolving the actual optimization task once the system is in place. Ciampa et al. quantified that 60% to 80% of the project time might be necessary to implement such a process, hampering the application in aircraft product development. Similarly, for MBSE system, large efforts are required to setup and operate them in complex development.

From such observations, stem the fundamental shift of focus: accelerating the development of complex systems to be engineered, by accelerating the deployment and operations of complex MDAO and MBSE design systems. This principle has been labeled by the author as the AGILE Paradigm, and has been demonstrated in the EU funded project AGILE [6]. However, in the AGILE project, the focus was on accelerating the deployment and operation of MDAO design system. In the follow-up project AGILE4.0, the focus is twofold:

1. Accelerating the deployment and operation of MBSE systems, to in turn accelerate the development of aircraft products
2. Streamlining the integration of MBSE and MDAO systems.

III. AGILE4.0 Project

The European Commission funded project has been recently launched: AGILE4.0 (2019-2022) [7]. AGILE4.0 inherits the AGILE Paradigm concept [6], leveraging digital engineering principles to accelerate the development life-cycle of complex systems in aeronautics.

The ambition of AGILE4.0 is to bring significant reductions in aircraft development costs and time-to-market through the implementation of an integrated cyber-physical aeronautical supply chain, from integrators and high-tiers suppliers to SMEs, leading to innovative and more sustainable aircraft products. In particular, AGILE 4.0 targets the digital transformation of main pillars of the aeronautical supply-chain, including design, production, certification and maintenance. To meet this challenge a Consortium of 18 industry, research and academia partners from Europe, Canada, Brazil, and Russia are collaborating together. Therefore, in AGILE 4.0 complex product development scenarios are investigated, integrating multiple stakeholders, and covering the complete development life cycle. The composition of the AGILE 4.0 consortium and the available capabilities permit to perform realistic investigations covering all the aspects of the aeronautical supply chain, in order to validate the AGILE 4.0 technologies. A representation of the domains addressed by the project and the Consortium are given in Figure 2.

Figure 2: AGILE4.0: overall concept (right), consortium (left). Focus is on accelerating the development of complex systems, by digital transformation of the aeronautical supply chain.

A. High Level Objectives and Performance Indicator

In order to achieve the high-level objectives, the following 3 elements are identified as high-level objectives (HLO):

1. **HLO-1:** Reduction of development time for innovative & Sustainable aircraft products
2. **HLO-2**: Reduction development costs for innovative & Sustainable aircraft products
3. **HLO-3:** Increasing competitiveness of the aeronautical supply chain

AGILE4.0 builds upon the MDAO technologies developed in the AGILE project, but focuses on the development of a Model-Based **MBSE-MDAO Framework** supporting the virtualization of multiple products (e.g. aircraft, engine and production tooling) and processes (e.g. design, manufacturing, certification, maintenance), through the development cycle. This includes the modelling of development scenarios, stakeholders involved, needs and requirements; the modelling of the aircraft architecture; the deployment of large-scale development and optimization processes; the modelling of the decision making and validation processes. In particular, the developed AGILE4.0 framework, introduced in this paper, focuses on streamlining the bridge between the systems engineering activities (MBSE) and the design and optimization activities (MDAO).

In order to measure the progresses of the AGILE 4.0 results toward the objectives, the following performance indicators (PI) have been set:

1. **PI-1:** Integration of at least **3 supply-chain levels** (e.g. OEM, Tier 1, Tier 2) in the developed MDAO workflows
2. **PI-2: 50% reduction** (SOTA provided by industrial partners) in iterations between design and manufacturing phase due to the virtual integration of design and manufacturing aspects
3. **PI-3:** Ability to include **at least 2 objectives for each domain** in all developed MDAO workflows, such to deliver Pareto fronts of optimal solutions rather than solutions optimized for single criteria

4. **PI-4: 30% reduction** (SOTA provided by industrial partners) in overall process development lead time due to the virtual integration of design, manufacturing and certification models
5. **PI-5: Zero time to reconfigure** (i.e. modify problem definition, and/or solution strategy and/or involved tools) a pre-established collaborative MDAO workflow

The relationships between the HLO and the PI are illustrated in Figure 3

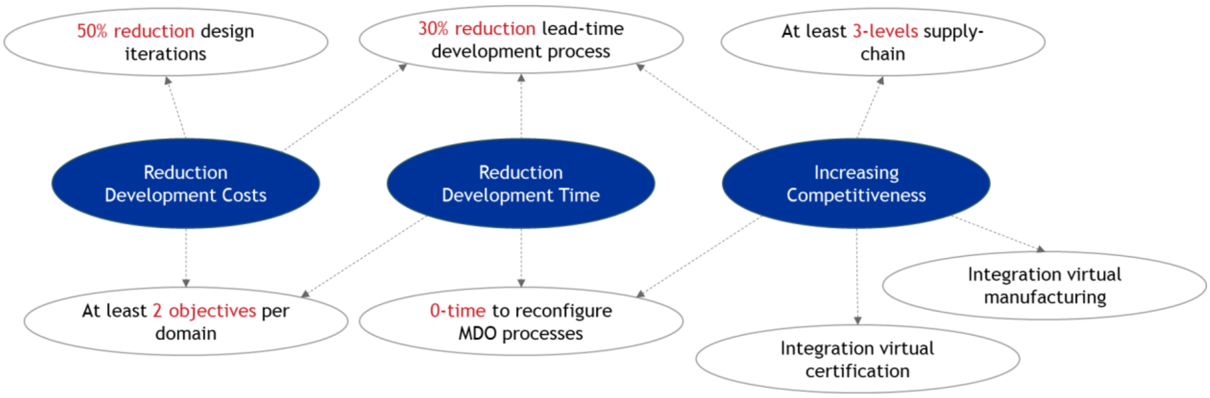

Figure 3 AGILE4.0 High-level objectives and Performance Indicators

B. Overview Project Structure

AGILE 4.0 is structured into three main layers, as illustrated in Figure 4:

1. **Application Cases** layer: AGILE 4.0 addressing **7 parallel aircraft application cases** investigated during the project. Each one is focuses on a specific aspect of the development life-cycle of an aeronautical system, i.e., design manufacturing, assembly, certification and maintenance. The products delivered by this layer, are the aircraft configurations under investigations and the results from the trade-off studies performed (e.g. certification vs performance).
2. **Specification, Modeling, Validation** layer: the development of the approach of the AGILE4.0 Framework, and the digital transformation of the development processes are coordinated in this layer. This layer is responsible to pull the requirements and needs from all the 7 application cases, and push them into the development of the enabling technologies layer. Once the enabling technologies become available this layer push them into the applications cases. The product delivered by this layer is the model-based approach driving the resolution of the application cases, whose overview is provided in the paper.
3. **Enabling technologies** layer: this is the production lab where the necessary (enabling) technical solutions to tackle the various application cases are developed. These include product and process models, the collaborative development IT platforms, optimization and decision-making techniques and various design tools to address the specific needs in the application cases. The product delivered here is the set of technologies which compose the AGILE4.0 design environment deployed for the resolution of the application cases.

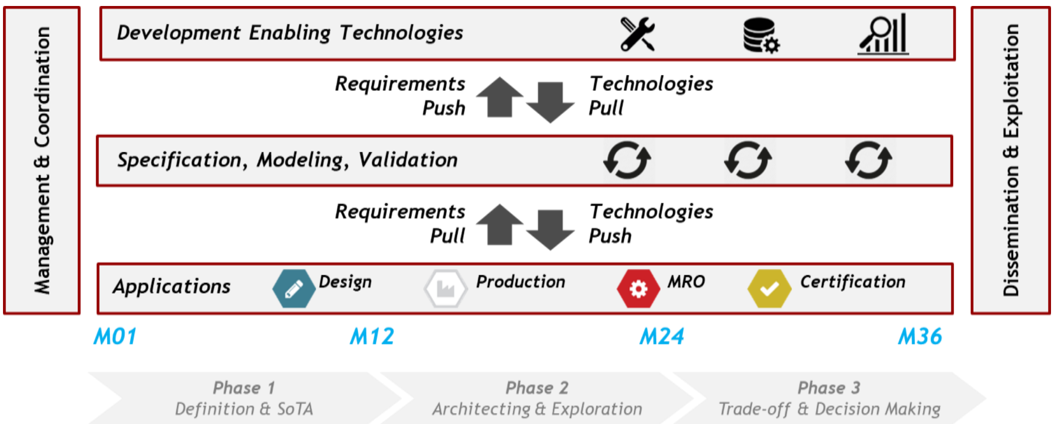

Figure 4 AGILE4.0 Overall Project Structure

The layers are clustered into 3 sequential phases.

- **Phase 1** (M01-M12): Definition and State of The Art (SOTA)
- **Phase 2** (M13-M24): Architecting and exploration
- **Phase 3** (M25-M36): Trade-off & Decision Making

C. Applications Cases

7 industry-driven application cases (AC) are investigated in AGILE4.0, all directly setup to validate the AGILE4.0 digital engineering solutions contributing towards the achievements of the project's objectives. All the application cases address the design of aircraft products with technology ready for Entry Into Service in the years 2025-2040, and represented in Figure 5

Figure 5 AGILE4.0 Configurations with EIS 2025-2040

. Each application case is driven by an industry owner which provides support for the requirements identification, scenarios definition, and validation of the solutions. In addition, for each application case an integrator is specified, who is in charge of leading the deployment of the AGILE4.0 Framework for the modelling of the application case, and of the integration of all the aspects needed to address the specific investigation.

Figure 5 AGILE4.0 Configurations with EIS 2025-2040

IV. Accelerating the Development of Complex Systems: a Conceptual Framework bridging MBSE and MDAO

In the context of AGILE4.0 project the DLR Institute of Systems Architecture in Aeronautics is developing a "model-based conceptual framework" for the streamlined development of novel and complex aeronautical systems. The envisioned concept aims to provide the capabilities to efficiently generate, evaluate, perform trade-off, and optimize, complex aeronautical systems accounting for large number of architectural and design choices through all the life-cycle. The objective is to accelerate the development time and reducing costs through modeling efficiency and automation, increased transparency and traceability of the design and decision-making process. Well established Systems Engineering (SE) provides extensive approaches supporting the development of complex systems (i.e. aircraft). Furthermore, as defined by INCOSE (International Council on Systems Engineering), a major goal of Systems Engineering is to reduce this "perceived complexity". In particular, in the recent years Model Based Systems Engineering (MBSE) approaches emerged as promising enablers. INCOSE expects in its vision for the year 2025 [8] MBSE transitioning from an early stage of maturity to the norm for systems engineering execution and enabling a better understanding of complex systems behavior much earlier in the product life-cycle.

Therefore, the conceptual framework here presented is based on the implementation of novel design methods and approaches, leveraging digital design engineering methods, in particular MBSE (Model Based Systems Engineering) and MDAO (Multidisciplinary Design Analysis Optimization), with focus on the seamless integration between them.

As already noted by van Tooren and La Rocca in [9], Systems Engineering and Multidisciplinary Design Analysis Optimization approaches are both aiming at supporting the product development process. SE supports the total engineering effort while MDAO helps finding the best parameter values for a pre-selected family of design solutions against quantitative requirements with mathematical tools. Therefore, MDAO should be seen as a tool within the SE context.

However, the way in which MBSE and MDAO links to each other, is a topic of discussion and current research. In the current framework the authors address both horizonal and vertical integration of MBSE and MDAO approaches, and details are explained in the following sub-sections.

A. Conceptual Framework – MBSE and MDAO Horizontal Integration (Phases)

The conceptual framework focuses on bridging the here so-called "downstream product design and optimization" phase of complex system development (such as occurring in a multidisciplinary design and optimization process) to the "upstream architecting" phase (such as occurring in systems engineering approaches). The framework's phases are shown in Figure 6.

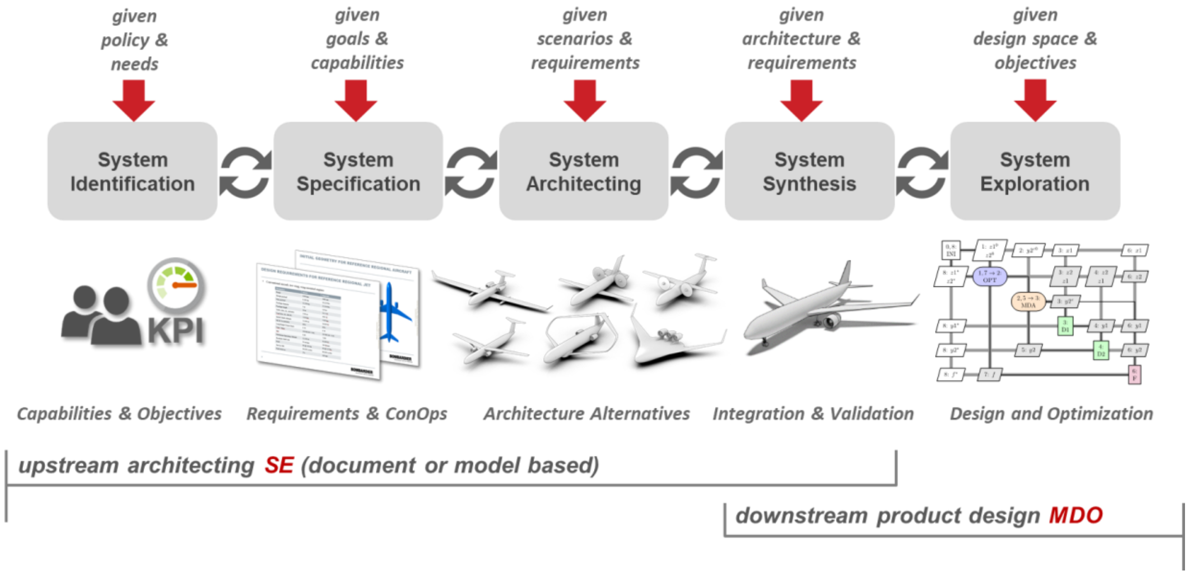

Figure 6 Complex System Development Framework: a bridge between upstream architecting phase (e.g. a systems engineering approach) and the downstream product design phase (e.g. a multidisciplinary design and optimization process) [1].

The proposed framework on one side focuses on the acceleration of ***upstream architecting*** phase, which includes activities such as the identification and trade-off of goals and capabilities which needs to be delivered, the specification of scenarios and requirements accounting for all the stakeholders involved, and for the design and optimization of the architecture of the System of Interest (SoI) under development, which could be a single system (e.g. an aircraft), or System of Systems. The corresponding activities are typically performed in SE approaches. On another side, the framework aims to accelerate the ***downstream product design*** phase, including the selection of the capabilities needed for every design stage (e.g. conceptual, preliminary, detailed), the integration of capabilities into a design processes, and the deployment and operation of design systems (e.g. computational environments), needed for the exploration of the design space and the selection of the optimal solution. The corresponding activities are typically performed in MDAO approaches.

Figure 6 illustrates the relationships of such generalized activities with SE (Systems Engineering) approaches (either document and\or model based), and MDAO approaches (either an exploration process and\or an optimization driven process). The shown bridge between the 2 phases is essential to accelerate the development of complex systems, and it is at the core of AGILE4.0 project.

The *MBSE* phases focus on the identification of needs and capabilities, for a given policy (e.g. sustainable aviation), the definition of scenarios and requirements accounting for all the stakeholders involved, the design and modelling of the architecture of the system of interest under development (e.g. an aircraft).

The *MDAO* phases address the design, exploration (and eventually optimization) for a given architecture and a given set of requirements. This includes the selection of the design competence (e.g. disciplinary simulations) according to the design stage (e.g. conceptual, preliminary, detailed), the integration into a design processes, the deployment of design system (e.g. computational environments), the exploring of the design space and the decision making about the optimum solution(s).

It is essential to realize the activities embedded in each phase are not executed in a streamlined and sequential approach, but are rather iterative. In addition, each phase focuses on a major domain, or perspective, of the development process, which is also determining the type of information which get consumed and generated, as well as the type of decisions which need to be taken, and the type of actors which are engaged in each phase.

Such a characterization has a deep influence on the modeling approach which has to be deployed, and on the modeling artefacts which are generated.

Enabling a seamless horizontal integration between perspectives and establishing a full traceability between artefacts exchanges is the major challenge to realize such a framework.

Table 1 summarizes the characterization of each phase, listing a generalized description of input consumed, output generated, and focus of the perspective.

Table 1 Conceptual Framework: MBSE-MDAO Phases Characterization

Phase	Input (I), Output (O), Perspective (P)	
Identification	I	Policy & Needs
	O	Capabilities which need to be delivered
	P	Stakeholders' value space
Specification	I	Given set of objectives
	O	SoI requirements and scenarios
	P	Operational space
Architecting	I	Given set of requirements and scenario
	O	Architectural Alternatives
	P	Architectural space
Synthesis	I	Given architecture and set of requirements
	O	Sized valid system
	P	Physical space
Exploration	I	Given design space and design strategy
	O	SoI properties
	P	Disciplinary space

1. *upstream architecting activities*

- **Identification (Stakeholders & Needs):** for a given policy (e.g. sustainable aviation) this activity addresses the identification of system stakeholders and their needs, delivering the set of goals, and capabilities which need to be met by the System of Interest under development. The System of Interest is addressed in the domain of the stakeholders, responsible for the validation.

- **Specification (ConOps & Requirements):** for a given set of goals & capabilities, and accounting for all the stakeholders involved, in this phase Concepts of Operations (ConOps) are elaborated to describe through scenarios how the system of interest will operate during its life cycle, delivering the set of requirements, which will need to be verified by the System of Interest under development. The System of Interest is addressed in the domain of its requirements.

- **Architecting:** for a given set of specified scenarios and requirements, this activity addresses the development and modeling of the architectural alternatives (functions and form) of the System of Interest under development (e.g. an aircraft), or for SoS (e.g. an urban air mobility solution). The architectures delivered include the functional (all the functions to be satisfied), the logical descriptions (mapping functions to logical components fulfilling the questions), and the instantiation of physical architectures (allocation of physical components to the logical ones). The System of Interest is addressed in the domain of architectural design space, and architectural alternatives.

2. *downstream product design activities*

The starting point of the design task to be solved is a **given set of design requirements and a given set of system architectural choices** (examples of given architectural choices are: selection of all-electric vs a conventional on-board-system, or the selection of a T-tail vs a low-tail layout, etc.). The underlying assumption is that those iterations on requirements and architectural choices have been performed ahead and delivered as frozen to the so-called “***downstream product design***” activities.

Therefore, the *downstream product design activities* include:

- **Synthesis & Verification:** for a chosen architecture and given set of requirements, this activity addresses the integration and the synthesis\sizing of the System of Interest. Such activity delivers the sizing and the verification of the design parameters of the physical architecture of the System of Interest under development. The System of Interest can be either initialized, analyzed and\or optimized. Such a synthesis is driven by a design and\or optimization process (either empirical or simulation-driven and of any level of fidelity\detail). The System of Interest is addressed in the physical domain.

- **Design & Optimization**: for a given physical architecture and defined design space, this activity includes the selection of the design competence (e.g. disciplinary simulations) according to the design stage (e.g. conceptual, preliminary, detailed), the integration into a design processes, the deployment of design system (e.g. computational environments), the exploration of the design space and the decision making about the optimum solution(s). This phase transfers the physical architecture (e.g. aircraft components) of the System of Interest into the “disciplinary domain” (e.g. aerodynamics, structure, etc.). Sub-activities of setup and execute a design and optimization process are inherited by the AGILE project [3].

B. Conceptual Framework – MBSE and MDAO Vertical Integration (Layers of Systems to be Developed)

The introduced framework aims to accelerate the development of a complex system, by leveraging digital engineering technologies. In addition to the horizontal integration, the framework also accounts for different types of systems which are interrelated to each other during the development of a complex system. The framework layered structure is shown in Figure 7, and each layer corresponds to a different type of system.

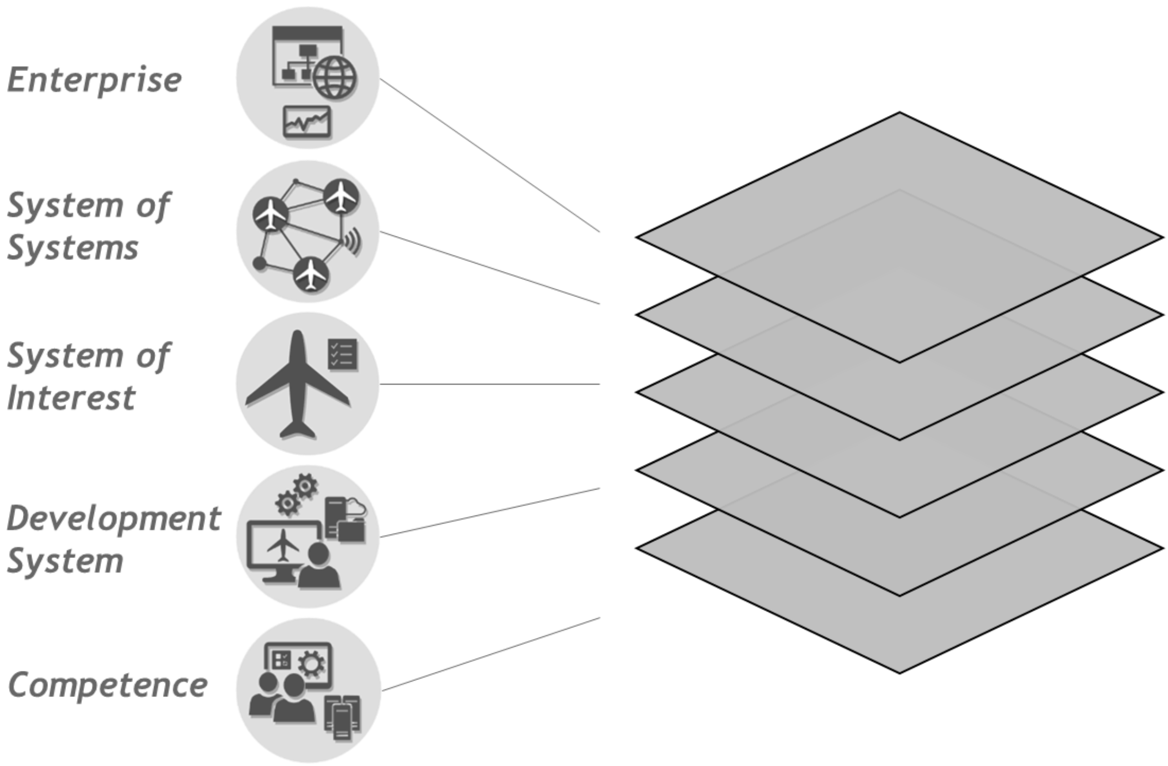

Figure 7 - Different types of Systems addressed by the framework

The identified five layers and major activities within each layer are:

1 *Enterprise layer:* modeling and optimization of goals and capabilities via value-driven decision-making approaches, enabling trade-off between policies by the enterprise.
2 *System of Systems layer:* architecting and designing complex System-of-Systems scenarios for a given set of capabilities to be delivered, enabling trade-off between concepts of operations.
3 *System layer:* Architecture Design and Optimization (ADO) of a complex system of interest for a given set of requirements and concept of operations, enabling trade-off between architectures.
4 *Development System layer:* deployment and operation of a development system and processes (e.g. Multidisciplinary Design Analysis and Optimization (MDAO) process) for the design and optimization of the system of interest, for a given architecture, design-for-X strategy (e.g. minimum cost), and dimensionality of the design space.
5 *Competence layer:* providing heterogeneous capabilities (e.g. disciplinary analysis) and services available, or to be developed, enabling system design and optimization.

Each layer addresses a specific type of system which is developed or in-use within the development life-cycle.
In addition, in the proposed framework in each layer the same MBSE-MDAO horizontal integration principles can be deployed recursively, aiming to a complete model-driven approach. Therefore, the MBSE-MDAO approach is deployed for both the development of the configurations illustrated in Figure 5, and for the development of the design systems (including the MBSE and MDAO system itself) such as in Figure 1.

C. MBSE-MDAO horizontal integration – Bridging Connections

The transition between phases implies a transfer of modeled heterogeneous information between the described perspectives. For the development of a complex system of interest, Often MBSE and MDAO are carried out as independent activities. This results in implementing supporting development systems which are not linked together, and the coherency between them can only being guaranteed manually.

In the Framework here presented, the authors have identified “bridging connections” which need to be established, and which are accounted in this Framework. Especially, we emphasize that the MDAO operations are mainly in the “disciplinary” domain.

MBSE Specification – MDAO Exploration: This connection relates the requirements specified for the “systems to be developed” with the design space which is explored during the MDAO process. This translates in ensuring that the requirements specified, can actually be provided by the disciplinary competences which are integrated in the design and optimization process. Especially when considering the instability of requirements, and how these might frequently evolve during a programme, it is essential to be able to quickly verify if the “development system” in use would need to cope with the new requirements, or would need to be changed.

MBSE Architecting – MDAO Exploration: This connection relates the architectural components (logical and\or physical) of the systems to be developed with the disciplines accounted during the MDAO process. This translates in ensuring that the components selected, are properly covered by the disciplinary competences which are integrated in the design and optimization process. Especially, different stages (i.e. conceptual., preliminary, detailed) of the design have different requirements on the granularity of the architectural model representation as well as on the fidelity of the physics phenomena which are modeled by the competences. Generating awareness on what is covered, and what is not covered by the development systems in-use is a key bridging connection.

D. Framework Technologies

AGILE4.0 project tackles the challenges related to the realization of such framework, and is developing the necessary technology enablers to established the MBSE-MDAO bridge discussed in this paper.
In particular the digital engineering technologies developed in AGILE4.0 focus on automate and accelerate the MBSE and the MDAO deployment and operational activities, which are needed for the development of the system of interest (e.g. aircraft configurations), as schematically illustrated in Figure 8.

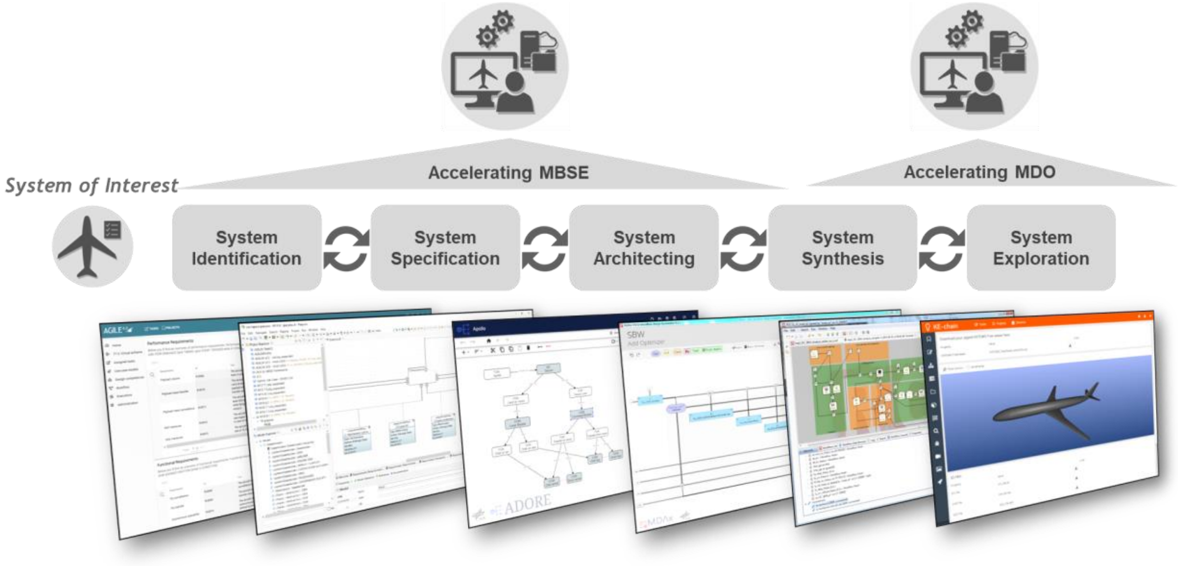

Figure 8 : MBSE-MDAO framework is supported by enabling technologies implemented in AGILE4.0. The focus is on accelerating the deployment and operation of MDAO systems and MBSE systems.

V. Framework Applications in AGILE4.0

As discussed in the previous Section, the MBSE-MDAO framework is recursively applied to different layers representing different kind of systems. Therefore, the conceptual framework described in the previous sections is also a model itself. Modeling such a framework means to define an Architectural Framework (AF) for each layer, which defines the underlying ontological concepts and perspectives driving the development of the system, as well as the deriving architecture of such a system and all the information which lead to such architecture (e.g. requirements, stakeholders). At this stage of the project, the framework focuses on supporting the System of Interest (i.e. the aircraft) and the development system (i.e. the MBSE and MDAO systems), by adopting a model-based approach. A brief overview is provided in the following sub-sections.

A. MBSE-MDAO Framework supporting the development of a "System of Interest"

The application cases are clustered into 3 following major streams, and or each stream, multiple study cases are addressed, and each study case is led by an industry owner. Figure 9 provides an overview of the 7 application cases with the corresponding owners, how these are clustered in 3 streams, and the focus of each stream.

1. **Production-driven stream:** here the focus is the integration of production-related objectives and constraints within the aircraft design and optimization process. Application case 1 focuses on manufacturing aspects, such as recurrent and non-recurrent (e.g. tooling) costs associated to different manufacturing techniques for novel concepts. Application case 2 focuses on supply-chain aspects, such as the optimal structure of OEM and suppliers, accounting for make or buy trade-off [10].

2. **Certification-driven stream:** here the focus is the integration of certification-related objectives and constraints within the aircraft design and optimization process. Application case 2 and 3 focus on the safety and maintenance aspects, due to the electrification of on-board systems and propulsion systems. Application case 5 focuses on certification aspects of the airframe, such as structural integrity as well as electro-magnetic compatibility effects and thermal risk assessment [11].

3. **Upgrade-driven stream:** here the focus is the integration of production-related objectives and constraints within the aircraft design and optimization process. Application case 6 focus on finding optimal retrofitting strategy, accounting for costs. Application case 7 focus on finding optimal commonality for a family design.

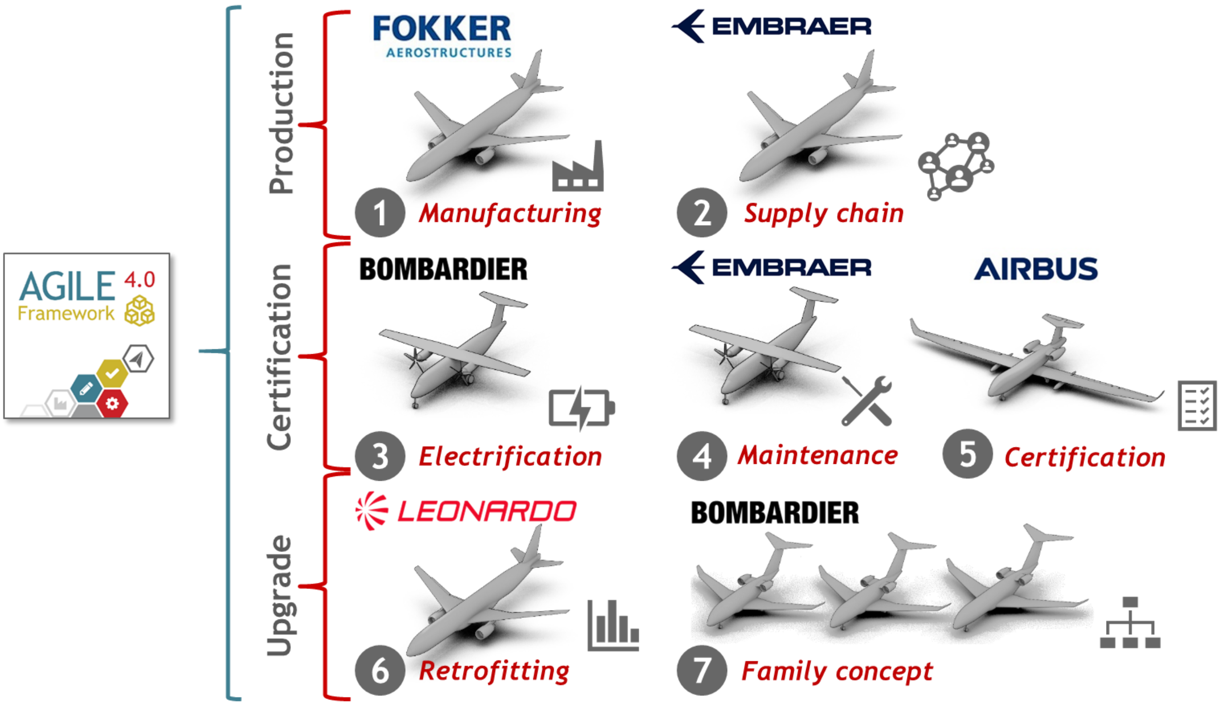

Figure 9 : AGILE4.0 - 7 industry-driven application cases driven by the AGILE4.0 Framework

All the application cases make use of the conceptual framework described in this paper, and enabled by the supporting technologies. In particular, details on the architectural framework corresponding to this layer are provided in Ref. [12]. An extract of the MBSE viewpoints specified by the architectural framework in this layers, and in-use for the requirements definition, is illustrated in Figure 10.

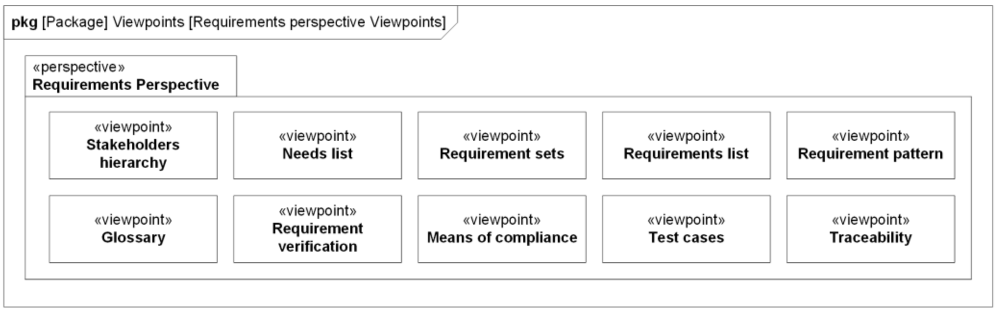

Figure 10 : Viewpoints of the architectural framework belonging to the requirement perspective [12].

B. MBSE-MDAO Framework supporting the development of a "Development System"

As well as MBSE promises to streamline the development of aeronautical systems, it is here advocated the potentials of MBSE to streamline the *development systems* supporting the design of complex aeronautical products. Specifically, this work leverages MBSE-driven approaches for the development of MBSE and MDAO development systems. More details on the architectural framework developed for this layer, and specifically for the MDAO systems, are provided in Ref. [13]. An overview of the architectural framework and type of MBSE models generated for the portion of the framework relative to the MDAO development systems is illustrated in Figure 11.

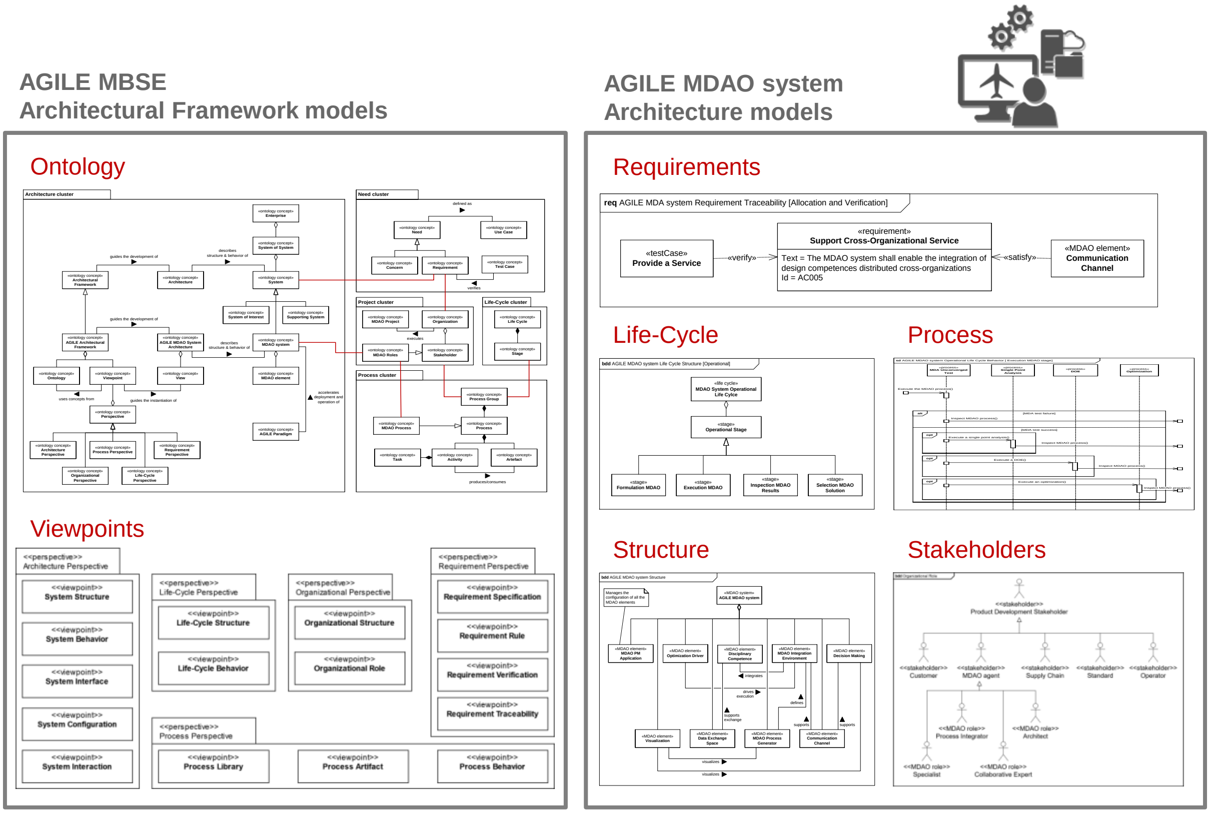

Figure 11 An MBSE approach for the development of a "MDAO design system" [13]

VI. Conclusions and Outlook

Aircraft manufacturers are preparing to develop the aircraft of the future, on one side as more environmental friendly, and on the other side as smarter, highly connected, embedding an ever increasing number of functionalities. However, as the systems to be engineered become more complex, the complexity of the decision process greatly increases, and it becomes more difficult to select design solutions through the development phases. The management of the "development complexity" requires a shift to a novel development paradigm for complex systems. More generally, we can state that in order to design the next generation of aerospace "complex systems", it is always necessary to develop along the next generation of supporting "design systems".

Therefore, the next generation of design systems will need to leverage digital design engineering technologies to accelerate the development time, minimizing associated costs, and at the same time maximizing value of the products under development.

This paper has introduced a framework which leverages model-based approaches and digital engineering technologies to accelerate the development of complex system. Such a framework is conceptualized in the EU funded project AGILE4.0 and introduces 2 major innovation elements:

1. MBSE and MDAO activities are streamlined and bridged (horizontal MBSE-MDAO integration).
2. The MBSE and MDAO activities are recursively applied to both the "system of interest" under development (e.g. the aircraft) and to the "development system" supporting the development of the system of interest.

The paper introduces an overview of the main concepts, and of the on-going investigations performed by deploying the framework described. AGILE 4.0 ambition is to provide the aircraft industry and research community with a way to model, assess, and optimize complex systems addressing the entire life cycle. The technologies developed will enable stakeholders and actors of the aeronautical supply chain to perform trade-offs which have never been possible to make before. Therefore, future publications will focus on the implementation aspects of such a framework, as well as on the results of the trade-off investigated. In addition, the framework is a model itself, and it is envisioned to make such a model available to the MBSE and MDAO community, as a blueprint for the development of complex systems.

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