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A MBSE Approach to MDAO Systems for the Development of Complex Products

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The research and innovation AGILE project has developed an approach, the so-called *AGILE Paradigm*, focusing on the acceleration of the deployment and operation of collaborative Multidisciplinary Design Analysis Optimization systems, which in turns can be exploited to accelerate the development of complex products, such as novel aerospace systems. Although the technologies developed for the implementation of the paradigm, have proved to reduce the deployment and operational time to more than 40% with respect to conventional MDAO approaches, the *AGILE Paradigm* has not been formalized and model by digital design engineering practices. This work introduces a novel approach leveraging MBSE principles to streamline the development of agile MDAO design systems, and establishing a bridge between MBSE and MDAO. Major outcomes here presented are the MBSE-driven models of the so-called *AGILE MDAO system*, representing the architecture, the requirements, as well as the organizational aspects, and all the interactions and activities implemented during the life-cycle stages of the MDAO system. The MBSE *Architectural Framework*, which defines the underlying ontological concepts and perspectives driving the development of the *AGILE MDAO system* model, are modeled and presented as well. The paper introduces for the first time the overall approach, as well as the high-level elements of the models developed, here represented by making use of *SysML* standard. The described approach is at the core of the recently launched project AGILE4.0, in which its scope will be expanded to cover the entire life-cycle of the development of complex aeronautical systems.

Nomenclature

AGILE	=	Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
AF	=	Architectural Framework
MDAO	=	Multidisciplinary Design Analysis Optimization (or MDO)
MBSE	=	Model Based Systems Engineering
OAD	=	Overall Aircraft Design
PIDO	=	Process Integration and Design Optimization
SE	=	Systems Engineering
SoI	=	System of Interest
SoS	=	System of Systems
SysML	=	System Modeling Language
TLAR	=	Top Level Aircraft Requirements

I. Introduction

Aviation is facing a profound reshaping, along many other industries. Major elements of disruption include a shift in customer demands, the vision for a zero-emission mobility, the proliferation of digital technologies under the so-called "fourth industry revolution". Ultimately, all these aspects are expected to lead to a new age of safer, fuel-efficient, more customized, and digitally optimized aeronautical systems. Therefore, 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.

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The development of complex aeronautical systems has to account for requirements and constraints on the air transport system as a whole, on the aircraft, and on all the individual components and technologies to be integrated. However, the ongoing trend of outsourcing, combined with the increasing shift of technical responsibility to high-tier suppliers, clearly introduces organizational, integration and communication challenges. Ideally every decision taken at each stage of the development should be evaluated along the entire life-cycle of the product under development, and for every stake holder involved. 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 poor integration of the various horizontal and vertical levels on which the current aeronautical supply chain is built, represents a major challenge, which is hampering the achievement of efficient and cost-effective development processes.

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 management of the *development complexity* requires a shift to a novel development paradigm for complex systems, and to the development of novel ***design systems***.

Such envisioned next generation of design systems 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.

Regarding Multidisciplinary Design Analysis Optimization (MDAO) [1], 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. However, although the individual technologies have been released open source, the *AGILE Paradigm* has **not been formalized and model** by leveraging digital design engineering practices.

Among the enablers supporting the digital design engineering transformation, Model Based Systems Engineering (MBSE) has grown in popularity in the last decade. Several aerospace, automotive, and defense organizations have already started the transitioning to MBSE approaches. Multiple benefits are advocated by MBSE practitioners, such as managing complexity, ensuring consistency and completeness, improving communications. Therefore, in product development context, Model Based Systems Engineering and Multidisciplinary Design Analysis Optimization are both aiming at supporting the development of complex systems (e.g. aircraft products).

Therefore, the work here presented proposes to leverage MBSE principles to streamline the development of *MDAO design systems* supporting the design of complex aeronautical products, and establishing for the first time **a bridge between MBSE and MDAO approaches**. Specifically, this work leverages MBSE-driven approaches for the development of *AGILE MDAO design systems*, modeling and formalizing the informal principles envisioned by the *AGILE Paradigm*, and therefore removing the aforementioned limitations.

Section II briefly recalls the AGILE project and the related *AGILE Paradigm*, which serves as foundation for the approach here presented. Section III presents the current challenges for the development of complex systems. Section IV introduces the overview of the "*model based conceptual framework"* for architecting, designing and optimizing complex aeronautical systems, which provides the overarching context to the specific research activities here presented. Thereafter, Section V focuses on the current gaps hampering the development of the next generation of "*design systems*", supporting product development, with focus on "*MDAO system"* and introduces the relationship with MBSE. Section VI and Section VII present the novel MBSE approach to the development of agile MDAO systems, and the major outcomes of such approach: the model of the "*AGILE Architectural Framework"* and the model of the "*AGILE MDAO system"*. In this paper the resulting models are represented by making use of SysML (Systems Modeling Language) standard [6].

The approach here presented is also the core of the newly launched EC funded project AGILE4.0 (2019-2022), briefly addressed in Section VIII, during which its scope will expanded to cover the entire life-cycle of product development, accounting for manufacturing, certification, maintenance constraints.

II. Overview AGILE Paradigm and AGILE Framework

AGILE project [2] has successfully developed Multidisciplinary Design Analysis Optimization (MDAO) technologies, enabling significant reductions in aircraft development costs and time to market, leading to cost-effective and greener aircraft solutions. The project, funded by the EU Horizon 2020 scheme, has started on June 2015 and concluded on November 2018. In order to enable the so-called "**3rd generation MDAO**" and to accelerate the deployment of large-scale, collaborative multidisciplinary design and optimization processes, a novel approach, the so-called "*AGILE Paradigm*" [7] [8] has been developed.

In MDAO applications, most of the speed-up increases are often sought in the performance of the optimization algorithms, or the disciplinary analysis. However, at the core of the *AGILE Paradigm*, the envisioned transformation has its focus on the acceleration of the deployment and the operation of cross-organizational MDAO systems, which in turns can be effectively exploited to accelerate the development of complex products, such as novel aircraft. This shift of perspective advocates that only once MDAO systems, which are often ad-hoc implementations, can be deployed with agility, then other speed-up benefits can be exploited in large scale applications. Therefore, the *AGILE Paradigm* is defined as a "blueprint for MDAO" guiding the deployment and the execution of collaborative "MDAO systems" for complex products practiced by cross-organizational design teams, distributed multi-site, and with heterogeneous expertise. In particular the *AGILE Paradigm* prescribes a series practices to accelerate and to facilitate the deployment of an MDAO system, it indicates how to streamline the operation of MDAO systems within the development of complex products, it defines the roles of all the stakeholders engaged in the development, and it indicates how to structure the interfaces and the interactions within the entire supply chain (data, models, and resources involved). The overall representation of the *AGILE Paradigm* structure and perspectives are illustrated in Figure 1. Details on the architectural elements of the *AGILE Paradigm* methodologies are reported in [5].

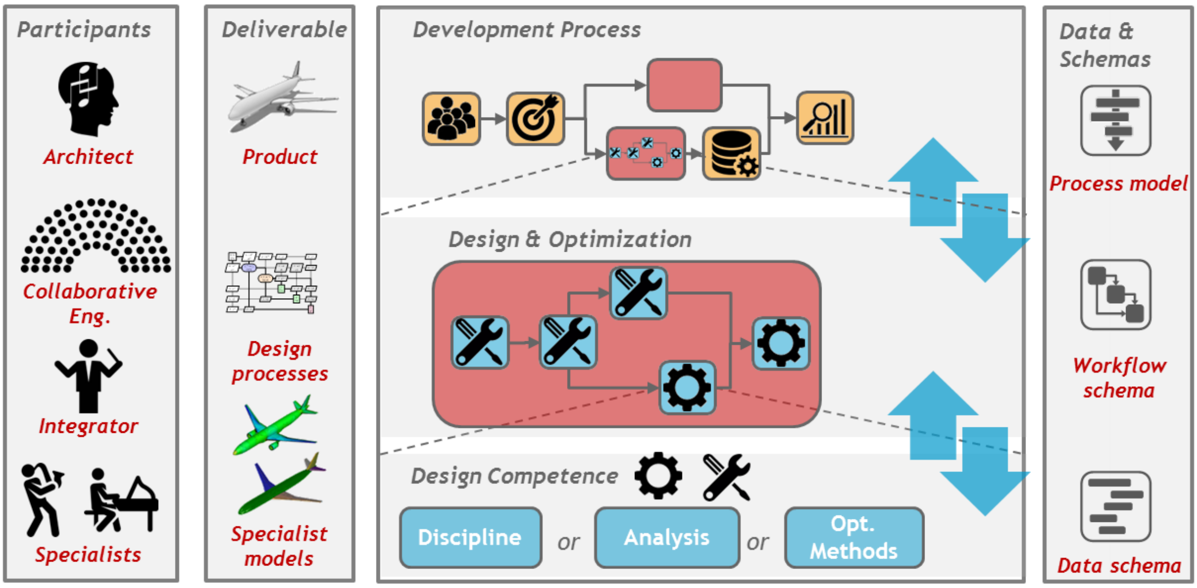

Figure 1 - AGILE Paradigm - Overall Structure of MDAO Systems [4].

The *AGILE Paradigm* has been formulated in a generalized way in order to be applicable to the design and optimization of aircraft (or sub-components), as well as to other complex systems. Furthermore, the AGILE project has developed a set of technologies enabling the implementation of the *AGILE Paradigm* approach [9] [10] [11] [12] [13] [14] [15]. The collection of all the technologies constitutes the "*AGILE Framework*". Each of the technologies targets a specific step of the AGILE Development Process, which establishes phases and tasks needed to deploy an MDAO system, as illustrated in Figure 2.

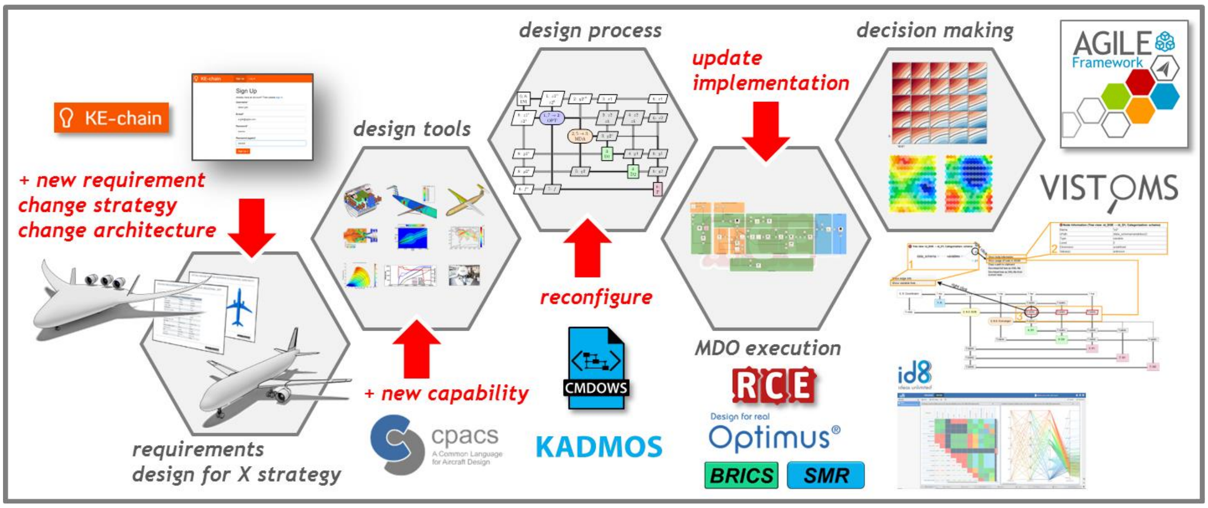

Figure 2 - AGILE Framework – Technologies implemented and supporting the setup and the execution of MDAO workflows.

The technologies developed in AGILE have enabled the consortium to deploy the MDAO systems for resolving multiple aircraft MDAO problems, starting with the specification of the Top Level Aircraft Requirements (TLAR), provided by the aircraft manufacturers, and including Overall Aircraft Design (OAD) processes targeting conceptual and preliminary development of aircraft with different EIS (Entry Into Service). An overview of the results on the applications is given in Ref. [16] [17] [18] [19] [20]. Figure 3 highlights main achievements, enabling the consortium to solve in 15 months 7 MDAO problems for unconventional aircraft configurations, and minimizing the time spent on deploying the MDAO systems.

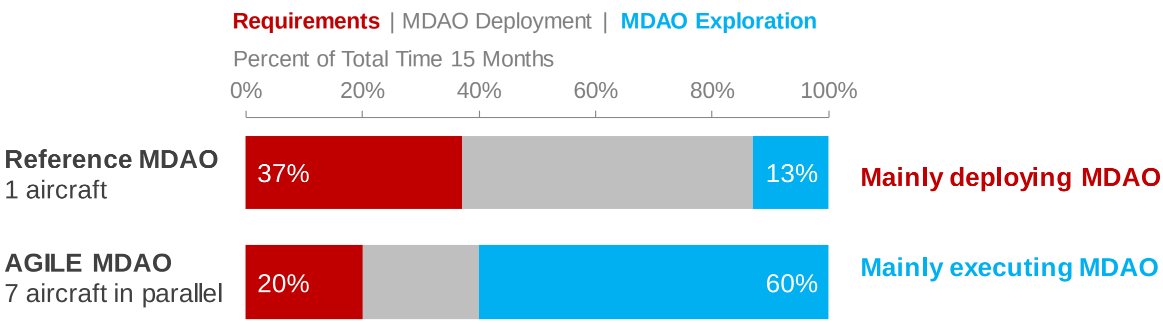

Figure 3 AGILE MDAO Approach: achieved time reduction. From 1 conventional aircraft MDAO problem solved in 15 months, to 7 unconventional aircraft MDAO problems resolved in parallel.

However, **two main limitations** have been identified in AGILE project:

1. the starting point of the MDAO problems resolved was a **given set of design requirements and for a given system architectural choices** (examples of given architectural choices are: selection of all-electric on-board-system, the selection of a strut-braced-wing system, etc.). The underlying reasoning assumed those iterations on requirements and architectural choices were performed ahead and delivered as frozen. However, this resulted in a given configuration, limiting the scope of the trade-off performed.

2. the overall paradigm, and the approach aiming to accelerate the deployment and the operation of the MDAO systems, has **not been formalized and modeled** by leveraging digital design engineering principles. Therefore, on one side the lack of formalization challenges the exploitation of the approach by externals using different technologies. On another side, the lack of a model for the "AGILE MDAO system's blueprint" challenges the implementation of changes or extensions (such as indicated by the first limitation), due to traceability difficulties.

The work here presented targets on removing the second limitation, which is also seen as the core to enable further expansions, as exposed by the first limitation, and already under development within AGILE follow-up project: AGILE4.0 [21].

III. Development Challenges of Complex Systems

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 developed become more complex, the complexity of the decision process greatly increases, and it becomes more difficult to select design solutions through the development phases. At the same time, supply-chains engaged in the development are becoming increasingly globalized, more complex and integrated as well. All these factors are contributing to drastically increase the development time and costs at every new generation of aerospace systems. Major development challenges are addressed in the following subsections.

A. Complexity Growth Challenge

Over time, large aerospace systems growth in complexity, in terms of components, software, interfaces, increasing the likelihood of unpredicted interactions. Although complexity can be defined in multiple ways, INCOSE defines a complex system as:

> "a system in which there are non-trivial relationships between cause and effect: each effect may be due to multiple causes; each cause may contribute to multiple effects; causes and effects may be related as feedback loops, both positive and negative; and cause-effect chains are cyclic and highly entangled rather than linear and separable" [22].

A common metric of complexity in engineering products is represented by the number of parts composing the system, and the number of Source Lines Of Code (SLOC) of software needed to enable the system's functionalities. Since 1960, as seen in Figure **4** the complexity of automobiles, integrated circuits, and aerospace vehicles has dramatically increased, but the total time of design, integration, and test for aerospace vehicles is increasing along the complexity, experiencing an opposite trend with respect to the other industries [23]. Looking at growth of complexity for aerospace vehicles, we can observe an ever increasing SLOC. An example is given by the evolution of aircraft flight decks in the last decades, for which software has been replacing the analogue elements of the avionic systems, towards all-glass cockpit designs. Although the cleaner design might suggest a simplification (and operational-wise it is true), it is also just hindering the extensively increased functionalities and automations which have been added at every new generation.

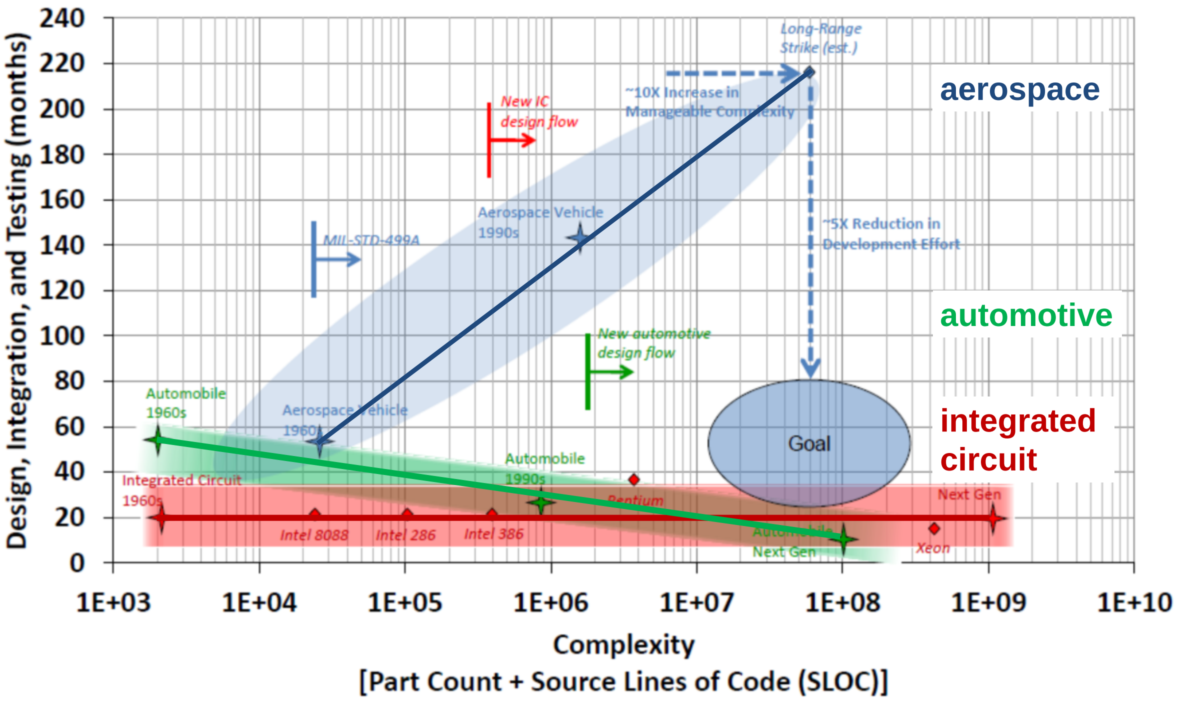

Figure 4 Relationship between complexity (expressed as SLOC) and development time (design, integration, testing) for complex systems in multiple industries (adapted from [24]). Aerospace is the only domain showing an ever increasing development times with increasing complexity.

B. Integration & Organizational Challenges

The advancements in digital technologies made available high performance computing infrastructures, sophisticated simulations covering multiple branches of flight physics, and effective data analytics supporting the decision making during the design. However, a major effort is the integration of the multidisciplinary competences into a coherent and consistent design process, such as needed to make use of MDAO methods. Furthermore, the development of complex products requires multiple iterations, and potentially for each candidate solution which is pushed downstream the development cycle, the design process integration effort need to be repeated multiple times. More details on challenges in establishing MDAO processes are reported in [5]. The early stages of an aircraft development program are characterized by high dimensionality of the design space which need to be explored, evaluating multiple competing concepts, as well as by large number of variations in requirements. For current aircraft programs the numbers of top-level requirements has grown to thousands, but only 18% remains stable during the program [25] leading to multiple redesign activities, added costs, extended schedule, and reduced performance. Furthermore, a large percentage of the program costs is committed at the very early stages of the design [26].

The integration challenges are even greater when the required design services for specific domains (e.g. disciplinary analysis) are provided by heterogeneous teams of specialists that are distributed among different organizations, and across nations. Moreover, the structure of organizations developing complex system, is often shaped along engineering disciplined (e.g. loads department within an aircraft manufacturer), and functions (e.g. marketing, designing, manufacturing), but it might be influenced by the share of work owned by the various organizational units or partners, adding extra boundaries and interfaces.

C. Communication & Socio-Technical Challenges

From the previous consideration, it clearly emerges that collaborative development of complex systems requires efficient and effective information exchange during the complete life cycle. Especially between humans and the tools operating together, such exchange needs to be correct and meaningful [27]. During aircraft developments, conflicts can easily emerge between cross-functional teams due to different interpretations of constraints and needs, leading to confusion and lack of understanding. Therefore, a consistent exchange and interpretation of information need to be guaranteed on multiple levels. On one level, the mental images of engineers, customers, operators and suppliers have to be aligned. On another level, the interoperability between the heterogeneous “design eco-systems” deployed within the development, needs to be ensured by all the involved parties. A need for interoperability might also emerge after a system has been developed, such as in a System of System (SoS) scenario.

Therefore, digital technologies can play a key role in reducing the degree of separation in information exchange, facilitating knowledge sharing between the many actors involved, and streamlining the integration efforts. However, a key element of the development is the human component. Although, traditionally the human operator is treated separated from the system, the engineering of these systems has to account for how people and organizations will use and misuse these systems [28].

IV. A Framework for Complex Systems Development

As highlighted in the challenges discussed in Section III, the development of modern complex systems needs to account for an ever increasing number of capabilities to be delivered, as well as for organizational boundaries, integration and communication challenges, and constraints stemming from all the stages of the product’s life-cycle. Furthermore, the system under development might need to operate in Systems of Systems scenarios, yielding interoperability requirements. Ideally every decision taken at each stage of the development should be evaluated along the entire life-cycle. The management of the “***development complexity***” requires a shift to a novel development paradigm for complex systems.

Recently, multiple aerospace organizations have announced initiatives which leverage digital technology enablers, with the objective to streamline the development of complex aerospace products. An example is the DDMS (Digital Design Manufacturing and Services) program launched by Airbus in early 2019 [29], in which modeling technologies, and systems engineering approaches are at the core of the development of the next products.

In this same context, the DLR “Institute of Systems Architecture in Aeronautics” is developing a novel “***model based conceptual framework”*** for architecting, designing and optimizing complex aeronautical systems. The envisioned concept aims to provide the capabilities to efficiently generate, evaluate, trade-off, and eventually optimize, the development of complex aeronautical systems accounting for large number of architectural and design choices through all the life-cycle.

The expected impact is a drastic reduction in time and costs associated with the development, via an increased transparency, efficiency, and traceability of the design and decision making processes.

The concept is supported by the development and implementation of novel design methods and approaches, leveraging digital design engineering and modeling technologies.

A novelty introduced in such a conceptual framework is to explicitly distinguish the "*System of Interest*" (SoI) which is under development (i.e. the aircraft), with the "*development systems*" (e.g. analysis and simulations capabilities, MDAO design systems, etc.) which are supporting the development of the SoI at the different stages of the life-cycle. In the following subsections the high level *scope* and the *structure* of the overarching conceptual framework are introduced, providing the context to the specific developments presented in this paper.

A. Framework Concept Scope

The foundations of the conceptual framework builds up on the experience gained during the EU project AGILE, and multiple DLR funded activities, with the focus to streamline and to accelerate the deployment and the integration of complex design and optimization processes for aircraft products (i.e. MDAO processes). However, the starting point of the design task to be solved is often a **given set of design requirements and a given set of system architectural choices** (examples of given architectural choices are: selection of all-electric on-board-system, the selection of a strut-braced-wing system, or more simply the selection of a T-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.

In the conceptual framework here presented, the target is to extend the scope of the design and optimization task, in order to account for all the trade-off performed through the "***upstream architecting phase***" of the development.

The *upstream architecting phases* include the identification of goals 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 modeling of the architecture of the system of interest under development (e.g. an aircraft), or for SoS (e.g. an urban air mobility solution).

The *downstream product design phases* address the design (and eventually optimization) for a given architecture and a given set of requirements. This includes the selection 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).

The envisioned overall concept, as shown in **Figure 5**, seeks to seamlessly bridge all the phases, enabling feedbacks and feedforwards, in order to quantify the impact of every choice along every stage. The MBSE approach to MDAO introduced in this paper, focuses on the *downstream product design*.

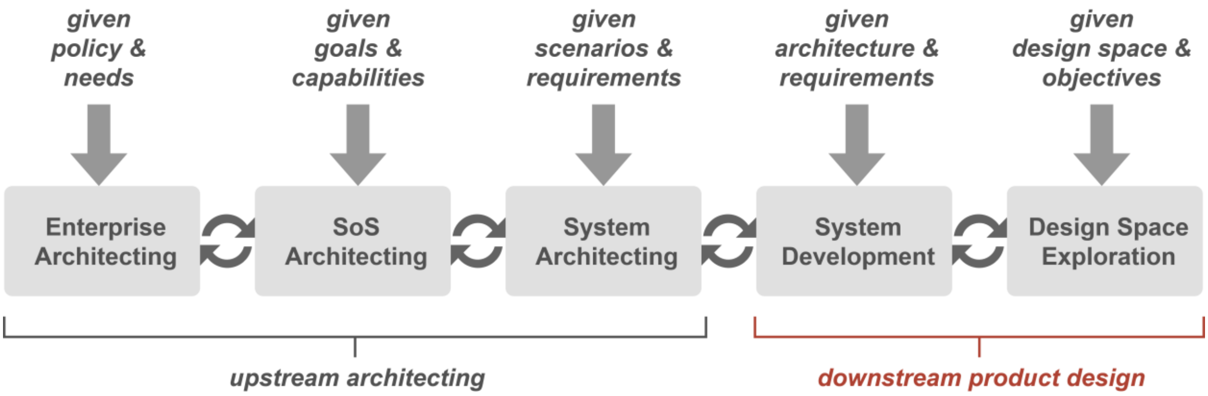

Figure 5 Model based conceptual framework: bridging the upstream system architecting development phases with the downstream product optimization phases (i.e. MDAO).

B. Framework Concept Structure

The architecture of the conceptual framework has a layered structure, as shown in Figure 6. 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 SoS scenarios for a given set of capabilities to be delivered, enabling trade-off between concept of operations.
3. **Complex System layer**: architecture design & 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. MDAO process) for the design and optimization of the system of interest, for given architecture, design for X strategy (e.g. minimum costs), and dimensionality of the design space.
5. **Competence layer**: providing heterogeneous capabilities (e.g. disciplinary analysis) and services available, or to be developed, enabling the system design and optimization.

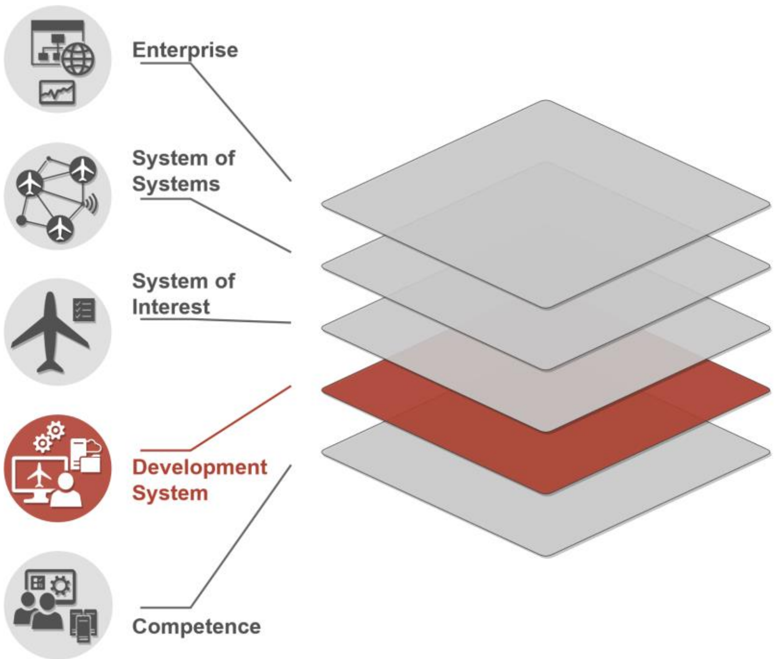

Figure 6 Model based conceptual framework: multi-layered structure.

Each of the inter-connected layer forwards the output and receives input and feedback information from the upper and the lower layers. Modeling technologies and systems engineering approaches are exploited to formalize every product, or service delivered at each layer, as well as processes and activities. Therefore, dedicated data models, exchanging format and ontologies are identified for each layer, and under development. Examples of ongoing works are the model of the "architecture design space" presented in Ref. [30], and the modeling environment for "design processes" presented in Ref. [31]. Finally, each of the layers is modeled accounting for multiple perspectives, focusing on a dedicated aspect of the layer, such as the architecture description, the stakeholders involved, the processes deployed, the data exchanged, etc.

As it can be observed from the conceptual framework structure, there is an explicit layer dedicated to the "development systems", which support and enable the design, but are usually treated within the "complex system" layer itself. Modeling such a layer explicitly, is a key to streamline the transition of the upstream architecting phases with the downstream product design activities.

The MBSE approach to MDAO introduced in this paper focuses on the development system layer.

V. Towards Modeling of agile "Design Systems" supporting "Complex Systems" Development

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. 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***". The relationship between *design system* and *complex system under development* is shown in Figure 7. 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.

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, 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.

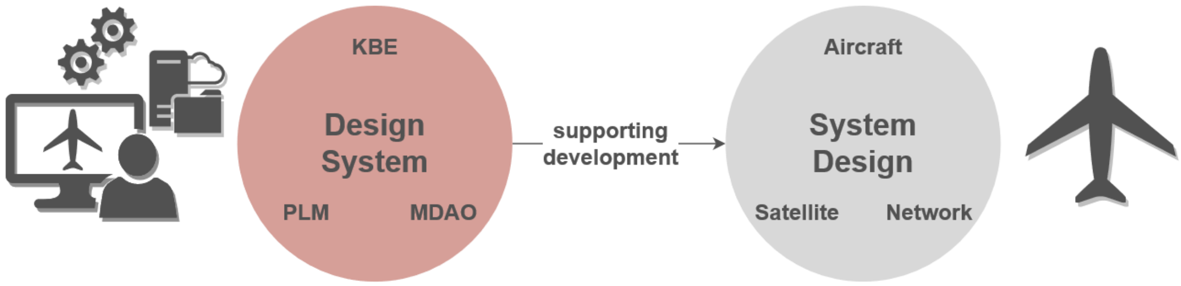

Figure 7 The development of the next generation of complex systems (e.g. the novel aircraft concepts), needs to be supported by the next generation of "*design systems*". MDAO systems are a specialized category of the design systems.

With respect to the conceptual framework introduced in Section IV, *design systems* belongs in the *development system* layer, and today more than ever the design systems should be interwoven and integrated in the whole products development structure, and along the entire product life-cycle. ***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*", and specifically for "*MDAO 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. Addressing the current generation of MDAO design systems, the authors have previously identified in Ref. [7] 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. Furthermore, rarely such a system would re-usable in other design and optimization tasks, resulting most of the time in an ad-hoc collection of individual technologies, loosely tied together by best practices and operational tacit knowledge.

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 design systems. Such a shift of focus is at the core of the AGILE Paradigm, formulated by the authors, and of the MBSE formalization approach here presented. In the next subsection, at first the need for agility for MDAO design systems is identified and discussed. Afterwards, the novel concept for "*MBSE approach to MDAO design systems"* is introduced for the first time.

A. The Emerging Need for Agility in MDAO Design Systems

Digital Technologies play a key role in streamlining developments, interactions, and communications along the entire product development and product life-cycle.

Analyzing the challenges discussed in Section III, and the shift of paradigm identified beforehand, it is possible to formulate and to extract a set of needs to be satisfied by the next generation of "MDAO design systems". Such high-level needs are represented in Figure 8, expressed as *use-cases*[4]. The diagram exposes the main need "provide agility for the design of complex product", which is decomposed in included needs, such as "streamline communication", "reduce the design integration efforts", "supporting operation in cross-functional teams". All of them include also the need "support human interaction" accounting for the socio-technical aspects. The use-case diagram used provides also the relationships between the *actors*[5] which interact with the MDAO system and are affected by the identified needs. Figure 8 shows only a selection of the high-level needs which have been identified by the authors, and reported in the current paper.

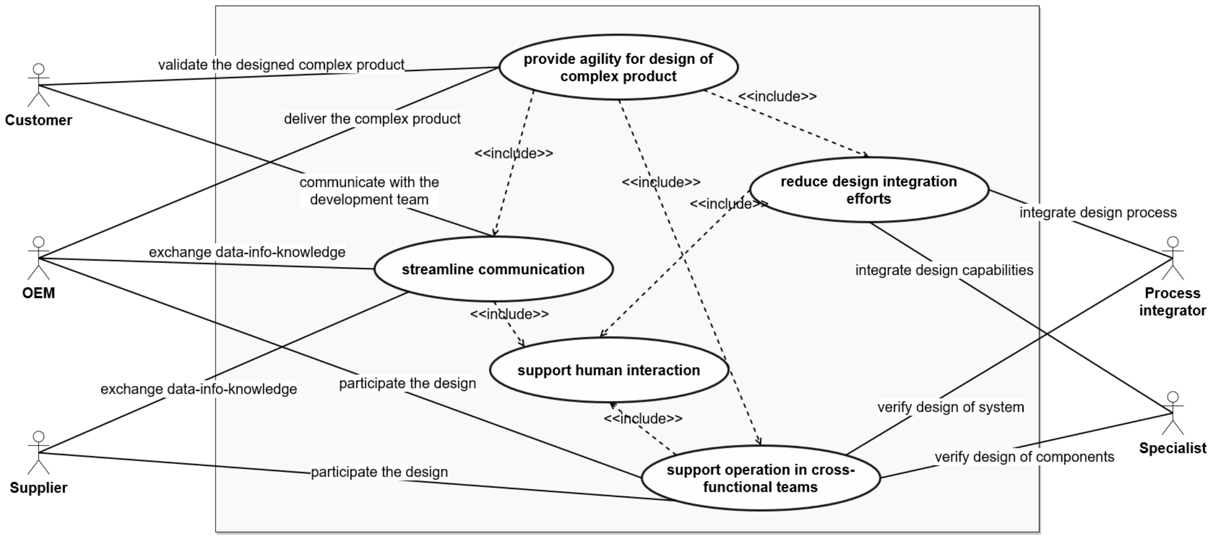

Figure 8 High level needs for the next generation of "MDAO design systems", interacting actors, and relationships.

A MDAO system which satisfied such high level needs is here labeled as an "***AGILE MDAO system***", and it is expected to enable the following capabilities:

- Supporting the management the increasing complexity of design and optimization processes.
- Reducing time and costs, to setup, implement, and execute cross-organizational and cross-national design and optimization processes.
- Accounting for the organizational structure, and facilitating interaction of different stakeholders within the design and optimization system, and the task under development.
- Supporting interoperability between multiple process integration design and optimization platforms, as well as facilitating the integration of pre-existing legacy processes.
- Supporting both the seamless integration of both automated and human-interactive simulations.

B. A MBSE Approach to MDAO Design Systems

As recalled in Section II, during the AGILE project a systematic approach has been developed with focus on accelerating the deployment and the operation of MDAO systems, and in turns accelerating the collaborative development of aircraft products. As outcome of such a shift of focus, the *AGILE Paradigm* has been formulated as a "blueprint for MDAO", which has proven to achieve drastic time saving to resolve collaborative MDAO problems, well above the 40% goal of the project [8].

However, although the *AGILE Paradigm* has been conceptualized as a solution neutral approach, and implemented by developing specific technologies within the project, the overall paradigm has never been formalized and modeled by leveraging digital design engineering practices. Such a limitation has challenged the implementation of the paradigm beyond the ad-hoc MDAO system deployed for the project, as well as challenged the expansion of its scope (as discussed in Section IV).

[4] use-case: element of UML\SysML, here employed to describe needs to be satisfied by "agile design systems"
[5] actor: element of UML\SysML, here used to identify stakeholders interacting with "agile design systems"

On another side, Systems Engineering (SE) provides extensive formalization 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 2025 [32] 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.

As already noted by van Tooren and La Rocca in [33], 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.

In addition, it is here observed that although extensive applications of (MB)SE approaches exist for the development of a product to be engineered (e.g. an aircraft, a software application), there is an open gap regarding the exploitation of MBSE approaches for the development of the aforementioned "*design systems*". Specifically there is a lack of MBSE approaches for the development of "*MDAO systems*", which are often developed in parallel with the product. Currently, even when a full model based and data driven implementations are in place, the relationship between the (MB)SE approach supporting the development of the product and the *MDAO system* is limited to the exchange of only input\output data, and there is a lack of integration with the architecture and the components of the *design system* itself.

This gap results into inconsistencies between the well formalized (MB)SE activities (e.g. requirements modeling and management, architecture modeling of systems or SoS) in the "*upstream architecting*" phases discussed in Section IV, and the design processes and systems (e.g. MDAO processes) which are implemented in the "*downstream product design"* activities.

As well as MBSE promises to streamline the development of aeronautical systems, it is here advocated the potentials of MBSE to streamline the development of *MDAO design systems* supporting the design of complex aeronautical products. Therefore, this work establishes for the first time **a bridge between MBSE and MDAO approaches**. Specifically, this work leverages MBSE-driven approaches for the development of *AGILE MDAO design systems*, modeling and formalizing the informal principles envisioned by the *AGILE Paradigm*.

This is an essential link, on one side fully aligned with the *AGILE Paradigm*, and therefore focusing on enhancing the agility of the *MDAO design system*, and on another side removing the limitation of the missing formalization and modeling step previously highlighted. The key relationships between MDAO and MBSE, as approached in this work, are represented in Figure 9.

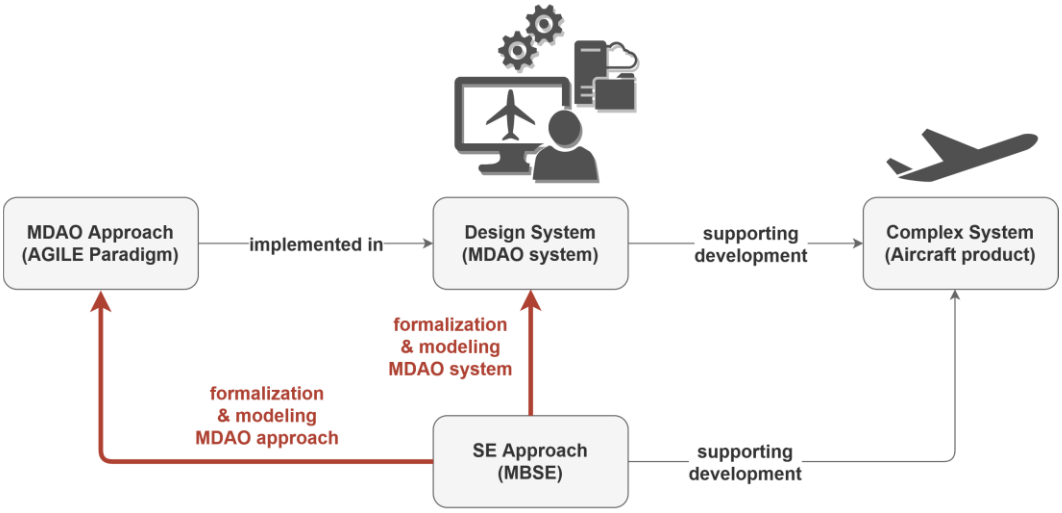

Figure 9 MBSE approach to MDAO. MBSE formalization principles are introduces to drive the development of MDAO systems, as conceived by the AGILE Paradigm.

As shown by the proposed relationships between MBSE and MDAO illustrated in Figure 9, a first objective is to leverage MBSE principles, to drive the development, formalization and modeling of the *MDAO design system* (or any other design system). A second objective is to leverage MBSE principles, to formalize the MDAO approach (*AGILE Paradigm* in this case) chosen for the development of the MDAO design system. This resulted into a novel formalized approach, according to MBSE principles, driving the development of complex MDAO design systems, which satisfy the agility needs previously discussed, and here called as "***AGILE MDAO system"***.

The resulting **MBSE-driven *AGILE MDAO system***, is represented by an architectural model. In SE the architecture of a system is the description of the system itself, capturing its structure (the form), its behavior (the function), and providing a mapping between its form and function [34]. Therefore, the architectural model developed for the *AGILE MDAO system*, contains the models of all its constituting elements, but also the models of all the deployment and the operational activities, along the entire life cycle of such MDAO system. All the logics and the dynamics of the *AGILE Paradigm* are therefore explicitly modeled, and visible.

The structured MBSE approach, leading to the development of the *AGILE MDAO system*, is formalized by a so-called "MBSE architectural framework", which defines and guides the development of the system's architecture itself. Such MBSE architectural framework has been developed as well, as specialized for the development of MDAO design systems.

Therefore, the here presented "**MBSE approach to MDAO systems**" is composed by two main elements:

- The **MBSE AGILE Architectural Framework**, which is the approach supporting the **model based** definition, and the development of a MDAO systems and its architecture. Such a framework defines a set of Viewpoints, and establishes the underlying concepts and nomenclature (or so-called ontology of the framework).

- The **MBSE AGILE MDAO System**, which is the outcome of the MBSE-driven development approach prescribed by the AGILE Architectural Framework. The core of the development is the modeling of the architecture of the *AGILE MDAO system*, representing a formalized and modeled blueprint for MDAO systems, describing both structure and behaviors. Such architectural model, is represented in a neutral and reproducible manner, as independent by the specific technologies needed for its implementation (in SE this concept is known as logical architecture).

In MBSE context, architectural frameworks are based on the fundamental concepts of "ontology", and "viewpoint", as described by Holt and Perry [35], and defines how to approach the development (or operation) of a system and its underlying architecture. Therefore, the relationships between the "*AGILE Architectural Framework*", the "*AGILE MDAO system*" and its architecture, is illustrated in Figure 10. Both these two elements are further described in the following Sections VI and VII. It can be observed in Figure 10, that the architecture, which describes the MDAO system, is composed by views. A view for a system exposes only a part of the system's model, its objects, relationships and constraints, with a determined focus. Typically the view can be expressed as a model, a document, a diagram, or any other format.

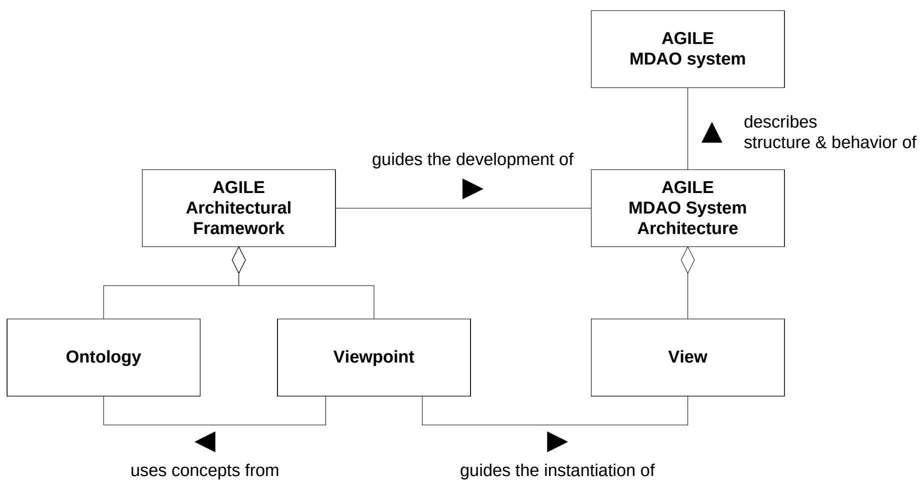

Figure 10 - AGILE MBSE Approach to MDAO system. The *MDAO system* is described by its *Architecture*, composed by *Views*. The development of the *Architecture* is guided by the *Architectural Framework*, which is composed by and *Ontology* and a set of *Viewpoints*.

It is necessary to underline that the objective of the *AGILE MDAO system* is to accelerate the time to market of complex products, by reducing the lead time needed to setup, deploy and operate a complex MDAO system. Therefore, its output is a design solution (or solutions) of an aeronautical system (e.g. an aircraft product) in a reduced amount of time, with respect to conventional MDAO systems.

The form of an *AGILE MDAO system* is formalized via a model representing its logical architecture. The objective of the *AGILE Architectural Framework* instead, is the realization of an MDAO system in a systematic and structured way, accounting for the agility needs. Therefore, its output is the architecture of an *AGILE MDAO system* (typically a digital engineering eco-system). The form of the architectural framework is a definition of concepts and viewpoints which are needed to model the *AGILE MDAO system*, and it is formalized by a meta-model itself. Table 1, highlights such a difference.

Table 1 AGILE Architectural Framework and AGILE MDAO system

AGILE Architectural Framework	AGILE MDAO System
High level goal: Supporting the development of AGILE MDAO design systems via MBSE principles.	**High level need:** Accelerate the deployment, operation, execution of collaborative MDAO design processes.
Form: A meta-model formalizing ontologies and viewpoints, specialized for MDAO design systems.	**Form:** MBSE architectural model of an AGILE MDAO design system.
When applied delivers: The architectural model of AGILE MDAO design systems following MBSE formalization.	**When applied delivers:** Product design solutions achieved with reduced lead time.

The value of developing a MBSE-driven model for *AGILE MDAO system*, is on one side to provide a blueprint which is proven to increase the efficiency of the development process of complex MDAO design systems, satisfying the agility needs. The modeling and formalization of the architecture of the AGILE MDAO system, facilitate the management of the complexity and increase the transparency in understanding logics and functionalities of such agile MDAO system, before any implementation. Even more relevant, such a model can support the understanding of the impact resulting by any change or extension in the MDAO system, whenever necessary. In addition models can be queried, for instance to check the consistency of the envisioned flow of information between computational elements of the design system itself, or between actors engaged into the operations of the MDAO system, such as between the disciplinary experts, and the process architects, before processes are actually executed during in the development program. Furthermore, the model of the AGILE MDAO system can be executed to investigate "what-if" scenarios, such as what happens if a certain element of the design system is not implemented in time, or it has to be replaced by an alternative one.

As mentioned, the model of the logical architecture for the developed *AGILE MDAO system*, provides a formalized description of the functionalities and components needed, as independent from the specific solutions, therefore facilitating the implementation of MDAO systems at different organizations (or consortium), but still providing a common view, and enabling inter-operability. In this perspective, ESA (European Space Agency) has launched the MB4SE (Model Based for Systems Engineering) initiative [36] aiming to define the architectural model of development systems which will support the development of space systems, as part of the efforts to streamline the common understanding among all the contractors, which typically own ad-hoc and legacy implementations of development systems.

VI. MBSE approach to MDAO Part I: Architectural Framework for AGILE MDAO Systems

This section focuses on the *AGILE Architectural Framework*, driving the development of A*GILE MDAO systems*. In SE context multiple so-called "Architectural Framework" (AF) have been developed in the last decades and exist today (e.g. Zachmann [37], DoDAF [38], TOGAF [39]), each with an own focus and specialization (e.g. acquisition phase, enterprise development, etc.). Although harmonization efforts are currently ongoing, such as for the UAF (Unified Architecture Framework) [40] developed by the OMG (Object Management Group), which attempts to unify several existing ones, interoperability is still a challenge and often ad-hoc frameworks are created, as extensions or adaptions of existing ones. Nevertheless, they all share the common principles of defining concepts and relationships (the ontology), as well as prescribing a set of viewpoints which can guide the modeling of the system to be developed (typically a hardware or a software product). Whereas, the specific contents, and especially the definition of the ontological concepts, can largely differ between frameworks, depending on the focus.

Therefore, the ***AGILE Architectural Framework*** here introduced is specialized to support the development of the architecture of *AGILE MDAO systems*, and it is based on a full MBSE approach, as defined by Holt and Perry [35]. The *AGILE Architectural Framework* establishes the "ontology", and the "viewpoints" necessary to model the logical architecture of *AGILE MDAO systems*. Despite most of the architectural frameworks being described as documents, *the AGILE Architectural Framework* is actually provided as a meta-model itself, and as such it has been developed by following MBSE principles as well, such as requirements identification and modeling. However, in this paper only the high-level outcomes of the *AGILE Architectural Framework* are briefly reported, as supporting the understanding of the *AGILE MDAO system* model. As already illustrated in **Figure 10**, two major elements compose the *AGILE Architectural Framework*:

- Definition and modeling of the high-level Ontology regarding the concepts which are used for the architecting of the *MDAO system*
- Definition and modeling of the Perspectives and the corresponding Viewpoints which need to be addressed when developing the *MDAO system*

All the models are here presented by making use of SysML (System Modeling Language) [6] notation developed by OMG, for the sake of clarity in displaying the information in a human readable format. However, the use of syntax and symbolism have been minimized and simplified for this specific paper. It also had to be underlined that the SysML diagrams which are shown in this paper, do not constitute the model itself, but just an exported representation of the model itself which has been implemented in dedicated modeling software environment. However, SysML has been chosen here to provide a neutral and standardized representation of the models of the *AGILE MDAO system* and *AGILE Architectural Framework*. Nevertheless, the content of the models might have been formalized by other formats as well. Finally, we note that it is not the purpose of this paper to present all the details of all the elements of the model, but only the high-level elements and specific details useful for the understanding of the novel approach presented. The complete model will be published afterwards in an appropriate format.

A. AGILE Architectural Framework: Ontology Definition

As a first step, the specific nomenclature and terminology which are used by the Architectural Framework need to be formalized, as well as the relationships between concepts defined. This corresponds to establishing the so-called framework's ontology. All the corresponding ontological elements have been described and implemented into a model. As noted beforehand, only a selection of the high-level ontology is here addressed, and briefly described. The overall high-level structure of the ontology model is represented in **Figure 12**, supported by SysML notation used for the diagram representation. As it can be observed in the figure, the ontological concepts composing the AGILE Architectural framework's ontology have been clustered in the following five areas:

1. MDAO system "Architecture cluster": containing concepts related to the definition of the MDAO systems elements, as well as its architectural description.
2. MDAO system "Need cluster": containing concepts related to specification, verification and validation of the requirements which need to be satisfied by the MDAO design system.
3. MDAO system "Process cluster": containing concepts related to all the activities which are performed within the setup, the deployment and the operation of the MDAO system, as well as all the artifacts produced by such activities.
4. MDAO system "Life-Cycle cluster": containing concepts related to the evolution of MDAO systems along its life-cycle.
5. MDAO system "Project cluster": containing concepts related to the management of the activities within a project using the MDAO system.

The model of the high-level ontology contains the definition of about 50 concepts, and only the high level ones for each cluster are represented into **Figure 12**. Each ontological concept, is expressed via a "*block*[6]" of the SysML notation, and therefore contains specific properties as well as operations related to that specific concept (not listed in this paper). When possible, the ontology concepts already available in standards have been employed, or extended, such as the (ISO\IEC 15288, DoD, INCOSE handbook, ISO\IEC 42010). An example is the concept of "Requirement" (in the "Need cluster"), which has been only extended from the standard SysML in order to include additional attributes helpful to streamline requirements management. Another, example is given by the "actor" concept of UML\SysML, which has been extended (as shown in **Figure 11**) for the AGILE MDAO ontology, in order to be able to differentiate specific roles, such as MDAO "Process integrator", or disciplinary "Specialist" which interact with the *AGILE MDAO system*. These roles where already identified in the *AGILE Paradigm*, however the modeling of the roles enables to add specific artifacts which are produced or consumed by the specialized actors, enabling to simulate several operational scenarios of the MDAO system under development.

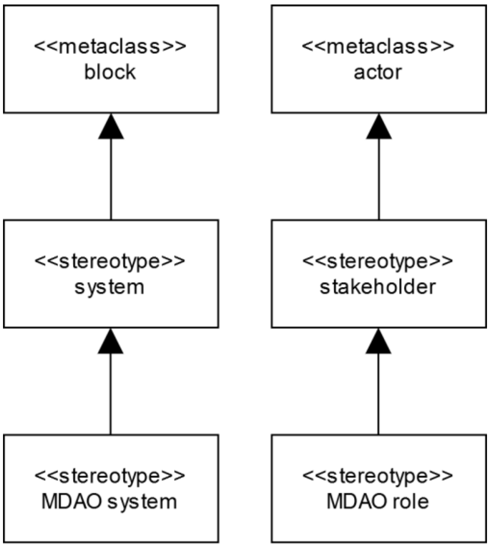

Figure 11 Examples of extension of standards concepts. As example the defined concept of actor is extended to stakeholder, and then to MDAO agent, to be able to differentiate specific roles interacting with the MDAO system. "MDAO agent" own specific properties.

All the ontology concepts have specific attributes (not listed here in this paper) and relationships. In **Figure 12** also a "red-thread" linking major concepts cluster has been left visible, to represent the connectivity between the ontological clusters. Finally, it has to be underlined that the ontological concepts can be used, and extended, to potentially architect other design systems.

[6] block: element of UML\SysML, here employed to represent the high-level ontological concepts of the *AGILE Architectural Framework*, and relationships between concepts

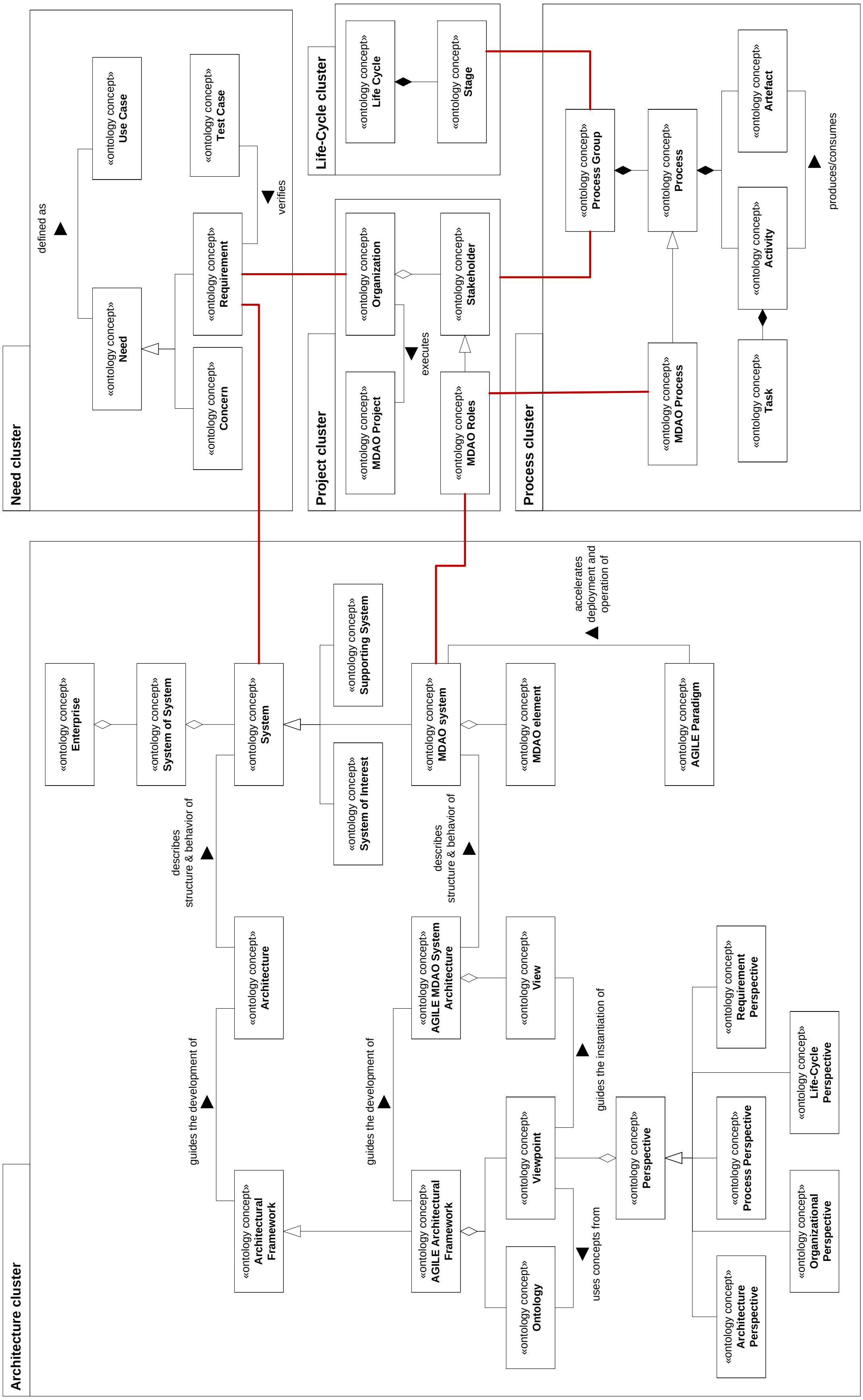

Figure 12 AGILE Architectural Framework – High-level Ontology concepts defined for the development of MDAO System. Main clusters are identified to group the concepts. Each concept is represented as a specialized "block", named "ontology element". Main relationships are illustrated between concepts in each cluster, as well as between clusters.

B. AGILE Architectural Framework: Perspectives and Viewpoints Definition

The second major element of the AGILE Architectural Framework, is the definition of a set of Viewpoints, facilitating to focus on determined aspects, or point of view, of the system under development, in this case an *AGILE MDAO design system*. As illustrated in **Figure 10** of Section V, the architecture of the model is described by a set of views. The rationale, the conventions, and the specified concepts which are used to model the view, are instead specified by the viewpoints. Also in this case, different architectural frameworks define their own set of viewpoints, according to the specialization of the framework itself. However, apart for the terminologies and the arrangements, similarities in the scope of viewpoints can be often observed between various architectural frameworks available.

Analogously to the ontology, all the viewpoints of the AGILE MDAO Architectural Framework have been clustered in main areas, known in MBSE as "Perspectives". Figure 13 is the high-level representation of the perspectives, represented by "*package*[7]" elements of the SysML notation. This representation highlights a containment relationship, of the viewpoints elements. The 5 perspectives identified are:

1. MDAO design system "Requirement Perspective"
2. MDAO design system "Life-Cycle Perspective"
3. MDAO design system "Process Perspective"
4. MDAO design system "Organizational Perspective"
5. MDAO design system "Architecture Perspective"

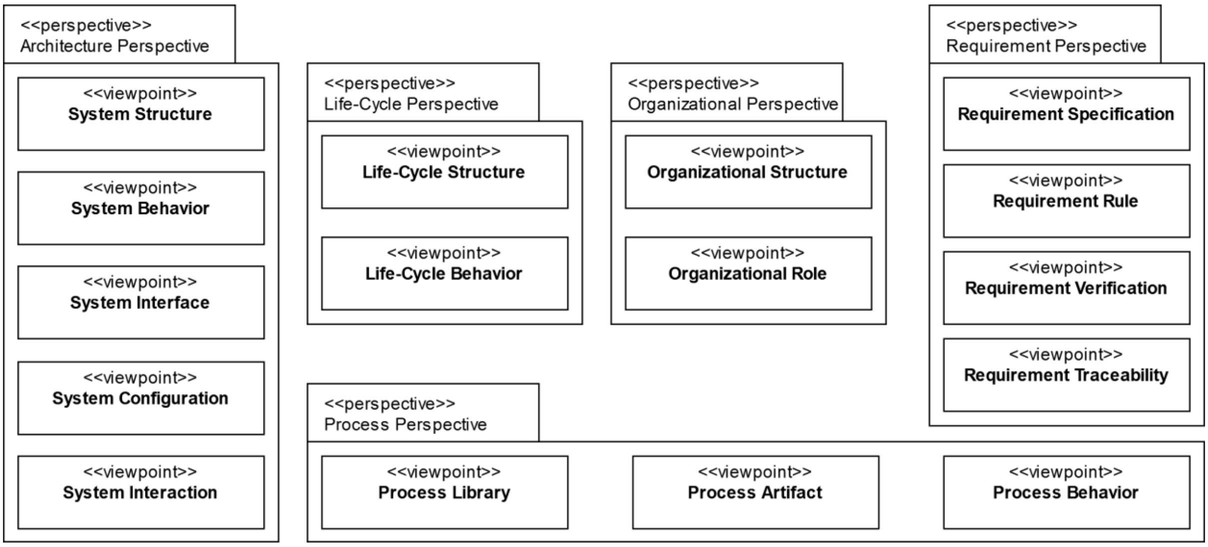

Figure 13 ***AGILE Architectural Framework*** **– Perspectives and Viewpoints for the development of MDAO System. For each perspective, represented as "*package" elements*, the corresponding contained main viewpoints are represented as *"viewpoint"* elements.**

It has to be noted that viewpoints can only make use of the concepts which have been defined in the ontology clusters. In addition, every viewpoint can be used to instantiate one of more views, specific for the system under development (in this case the *MDAO design system*). Furthermore, all the viewpoints defined by the AGILE Architectural Framework, are fully modeled as well in the meta-model, including the rules on how to build-up the corresponding views, or the notation syntax which should be used. Therefore, these can be easily used to verify that the instantiated views describing the architecture of the *MDAO design system* (or eventually other design systems) are conformal to the rules. Finally it is stressed that a Viewpoint identify only the focus, or "a specific glass" to look at the system under development, but it does not prescribes the contents of the instantiated View, which instead is specific for the system. An example of a Viewpoint, named "Requirement Specification" is given in Figure 14, where a series of tags provide a summary of the rational and purpose of the specific viewpoint. In this case Viewpoint is the same ontological concept as described by the SysML standard, and therefore easily represented by the SysML Viewpoint diagram element itself. Nevertheless, as for the other ontological concepts, the diagram is just a visual representation, whereas the model behind it enables to provide formal references to other ontological concepts, such as for instance to the stakeholders which are modeled.

[7] package: element of UML\SysML, here employed to represent the Perspectives of the *AGILE Architectural Framework.* Perspectives contain Viewpoints.

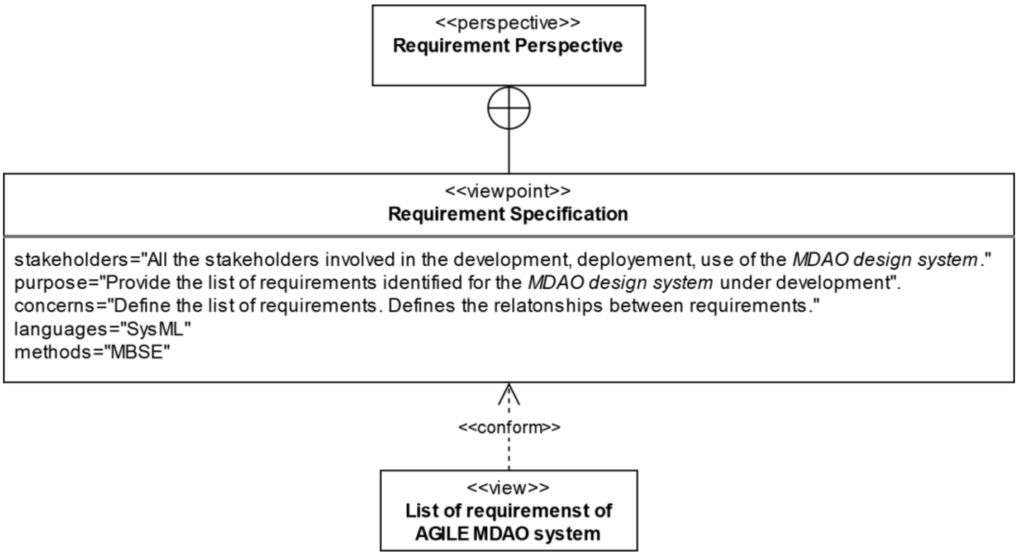

Figure 14 Viewpoint ontological concept, represented by a SysML "*viewpoint*" diagram construct. Goal of the viewpoint is to provide purpose, rational, and rules to guide the instantiation of specific views for the model of the system under development. This example shows a specific instantiated "*view*", named "list of requirements of AGILE MDAO system", which has to be conformal to the "*viewpoint*" "Requirements Specification".

In the following subsections, for each Perspective defined by the *AGILE Architectural Framework*, the contained Viewpoints are listed, and the rationale behind briefly described. Although, such a rationale might seem applicable to generic systems to be developed, in this paper perspectives and viewpoints are specialized for *MDAO design system*.

1. MDAO design system "Requirement Perspective"

The *Requirement perspective* contains all the models of all the viewpoints which have to be considered to describe the needs and requirements of the *AGILE MDAO system* to be developed. The perspective includes the definition of the requirements and relationships, as well as allocation to stakeholders which are responsible for the definition, the verification, and the validation. The list of the main viewpoints and the corresponding underlying rational is briefly summarized in Table 2. It is underlined that the viewpoints only provide the framework to develop the requirements of a *MDAO design system* under development, and not the specific requirements of the *MDAO design system* itself.

Table 2 Architectural Framework: MDAO Requirement perspective

MDAO Need perspective	
Viewpoint	**Rationale**
Requirement Specification	Defining a structured list and hierarchy of requirements of the MDAO system, and relationships with stakeholders.
Requirement Rule	Defining the rules according to which the requirements need to be specified, such as categories, and syntax to adopt.
Requirement Verification	Representing the means of compliance defined for the verification of the requirements.
Requirement Traceability	Establishing the traceability between elements of the MDAO system, the originating requirements, and the verification elements.

2. *MDAO design system "Life-Cycle Perspective"*

The *Life-Cycle perspective* contains all the models of all the viewpoints which have to be considered to describe the evolution of the *AGILE MDAO system* to be developed. The perspective includes the definition of life-cycle, the corresponding composing stages, as well as the interactions between the different stages. The list of the main viewpoints and the corresponding underlying rational is briefly summarized in Table 3. It is underlined that the viewpoints only provide the framework to develop the life-cycle model of a *MDAO design system* under development, and not the specific life-cycle of the *MDAO design system* itself.

Table 3 Architectural Framework: MDAO Life-Cycle perspective

MDAO Life-Cycle perspective	
Viewpoint	**Rationale**
Life Cycle Structure	Defining the stages composing the MDAO system life-cycle. Multiple life-cycle models can be defined.
Life Cycle Behavior	Representing the interactions between the stages of a life-cycle model, as well as between interactions within each stage.

3. *MDAO design system "Process Perspective"*

The *Process perspective* contains all the models of all the viewpoints which have to be considered to describe the activities, and tasks supported by the *AGILE MDAO system* to be developed. The perspective includes the definition of task, as well as the interactions between artifacts which are produced and consumed by the tasks, and between the stakeholders involved. The list of the main viewpoints and the corresponding underlying rational is briefly summarized in Table 4. It is underlined that the viewpoints only provide the framework to develop the processes models of a *MDAO design system* under development, and not the specific processes of the *MDAO design system* itself.

Table 4 Architectural Framework: MDAO Process perspective

MDAO Process perspective	
Viewpoint	**Rationale**
Process Library	Defining the list of processes related to the deployment and operation of the MDAO system, and corresponding activities and artifacts.
Process Behavior	Representing the activities for each process, and the interaction with the stakeholders involved as well as the artifacts produced/consumed.
Process Artifact	Representing the relationships between the artifacts involved in a process.

4. *MDAO design system "Organizational Perspective"*

The *Organizational perspective* contains all the model of all the viewpoints which have to be considered to describe the structure of the organizations involved in the deployment and operation of the *AGILE MDAO systems* to be developed. This includes the structure and relationships between stakeholders and organizational units, as well as the definition of prescribed roles which can be identified in MDAO problems. The list of the main viewpoints and the corresponding underlying rational is briefly summarized in Table 5. It is underlined that the viewpoints only provide the framework to develop organizational model of a *MDAO design system* under development, and not the specific organization of the *MDAO design system* itself.

Table 5 Architectural Framework: MDAO Organizational perspective

MDAO Organizational perspective	
Viewpoint	**Rationale**
Organizational Structure	Defining the structure of the organization(s) and stakeholders involved in the life-cycle of the MDAO system, and their relationships.
Organizational Role	Defining the explicit roles to stakeholders, interacting during the deployment and operation of MDAO system. Each role is engaged in specific activities and responsible for specific artifacts.

5. MDAO design system "Architecture Perspective"

The *Architecture perspective* contains all the model of all the viewpoints which have to be considered to describe the structure and the behavior of the *AGILE MDAO systems* to be developed. This includes the structure and hierarchy of the elements composing the MDAO system, as well as the definition of the interfaces and the interactions between components, and with the stakeholders involved. The list of the main viewpoints and the corresponding underlying rational is briefly summarized in Table 6. It is underlined that the viewpoints only provide the framework to develop the architecture model of a *MDAO design system* under development, and not the specific architecture of the *MDAO design system* itself.

Table 6 Architectural Framework: MDAO Architecture perspective

MDAO Architecture perspective	
Viewpoint	**Rationale**
System Structure	Defining the elements of the MDAO system, the relationships, properties and functions.
System Behavior	Representing the functional behavior for the MDAO systems and its constitutive elements.
System Interface	Identifying the interfaces between the system's elements.
System Configuration	Defining the configurations between the system's elements and the corresponding interfaces.
System Interaction	Representing the interactions between the system's elements, and with the stakeholders, during the deployment and operation.

VII. MBSE approach to MDAO Part II: Architecture Model of AGILE MDAO System

The MBSE ***AGILE Architectural Framework*** is here employed to drive the development of the MBSE model of the ***AGILE MDAO system*** and its architecture. The architecture of the resulting *AGILE MDAO system* is modeled via a set of views instantiated from all the viewpoints prescribed by the *AGILE Architectural Framework*. As well as for the framework, in this paper the authors present only selected views for each of the perspectives. The scope is to highlight the logic behind the application of the MBSE-driven approach for the development of the *AGILE MDAO system*. As well as for the model of the ontology, the complete set of model's views will be released in a suitable format.

A. AGILE MDAO system: Logical Architecture Model Views

This section contains a selection of the views which have been developed and describe logical architectural model of the AGILE MDAO system. Although, the model views are presented in a sequential order, the actual development and modeling processes of the MDAO system's views it is of iterative nature. It is noted that every element contained in each view, is the instantiation of the ontological concepts contains in the framework's ontology. The consistency and correctness (syntactic and semantic) is ensured by the modeling approach, which is a key in accelerating the development of complex MDAO design systems.

1. MDAO design system "Organizational Perspective"

As mentioned, the AGILE MDAO system allocates specific roles within the team involved in the deployment and operation of the MDAO system. Figure 15 represents one of the views instantiated for the "Organizational Role" viewpoint (Table 5). The view focuses on the so-called MDAO agents, which are engaged with the deployment and the operation of the *AGILE MDAO system*. Each of the MDAO agent, modeled by "*MDAO role*" (a concept from the organizational ontology cluster) is responsible for specific artifact produced/consumed (not represented in the diagram) by the *AGILE MDAO system*. Other stakeholders, such as "Customer", are also modeled, since they provide input to requirements of the product under development, which might affect choices in configuring the AGILE MDAO system, for instance a time budget.

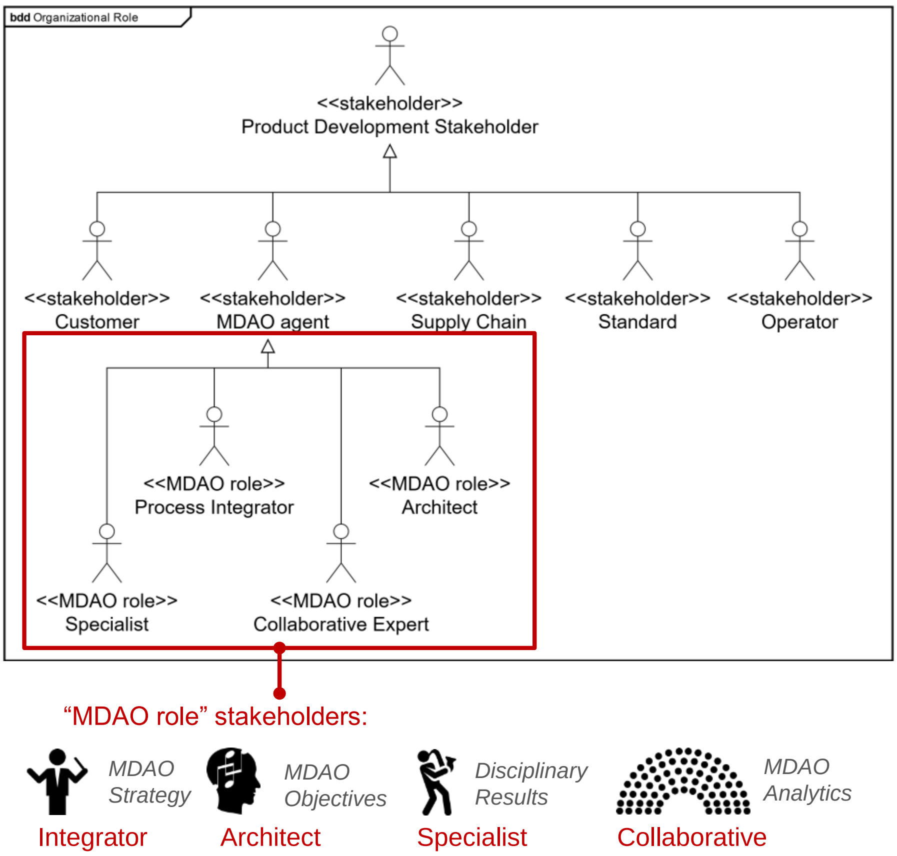

Figure 15 *AGILE MDAO System* – Organizational Role View: identified stakeholders interacting with the MDAO system during a product development program. "MDAO role" actors are a specific type of stakeholder, which are engaged with the deployment and the operation of the MDAO system.

2. MDAO design system "Architecture Perspective"

During the development of the *AGILE MDAO system*, a list of functionalities is prescribed and a list of requirements has been specified. Afterwards, a mapping of these functions to components has been modeled. Figure 16 represents one of the views instantiated for the "System Structure" viewpoint (Table 6).

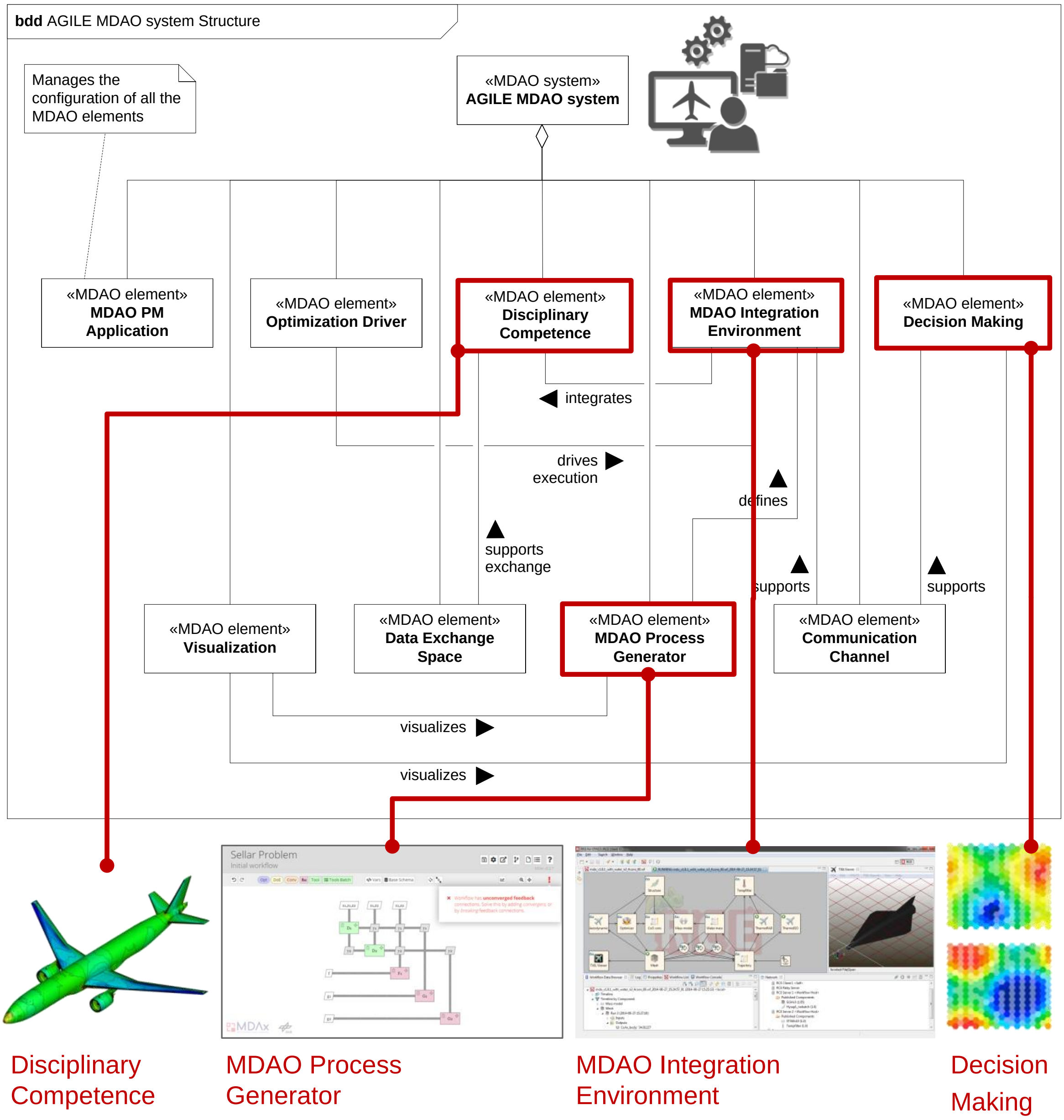

Figure 16 *AGILE MDAO System* – System Structure View: high-level representation of main elements composing the AGILE MDAO system. Every "MDAO element" has associated specific properties and operations (not shown in this diagram).

The view (expressed as a simplified SysML block definition diagram) shows the main elements which composes the *AGILE MDAO system*:

- **MDAO Integration Environment**: the execution environment (i.e. PIDO) of the MDAO process.
- **MDAO Process Generator**: the automated generator of the MDAO process and partitioning strategy.
- **Optimization Driver**: the logic driving the execution strategy of the MDAO process (e.g. a gradient based optimizer, a design of experiment, etc.).
- **Disciplinary Competence**: the design\analysis competences which are needed integrated in the MDAO process (e.g. an aerodynamic solver, a mission performance analysis, a subject matter expert assumption).

- **Data Exchange Space**: the space where data are exchanged between the elements of the MDAO system (design competences output, optimization results, etc.).
- **Communication Channel**: the communication channels and protocols enabling data exchange (e.g. between design competence and the data exchange space, between MDAO integration environment and stakeholders, between decision making and stakeholders, etc.).
- **Decision Making**: the data analytics services for the decision making processes (e.g. on the MDAO design space results, on the type of design competences to use).
- **Visualization**: the visualization services of data and processes involved (e.g. product model, disciplinary results, optimization results, MDAO processes, etc.).
- **MDAO PM Application**: the management cockpit for configuration of the MDAO system by the stakeholders involved (e.g. selection of design competences, definition of the MDAO problem, etc.).

Each element owns specific properties, sub-components, performance metrics, as well as a list of operations to be performed by the element.

3. MDAO design system "Life-Cycle Perspective"

A life cycle model has been developed for the *AGILE MDAO system* itself. In fact MDAO system, as any other system, need to be implemented, operated, updated, and eventually disposed. Example of typical updates of a MDAO system are implemented when better disciplinary competences become available, or with the introduction of novel optimization algorithms, or simply due to the updates of PIDO integration platform. The *AGILE MDAO system* defines multiple life-cycle models:

- MDAO system **Development Life-Cycle**: the overarching evolution of an MDAO system which will be employed within a project. Similarity to the standard ISO\IEC 15288 [41] system development life cycle has been retained.
- MDAO system **Deployment Life-Cycle**: describing the deployment of the MDAO system which needs to be instantiated for the resolution of a specific MDAO study.
- MDAO system **Operational Life-Cycle**: describing the operation of the MDAO system, in order to explore the design space and solve the MDAO problem.

Figure 17 represents one of the views instantiated for the "Life-Cycle Structure" viewpoint (Table 3), representing the structure of the "Operational Life-Cycle" (expressed as simplified SysML block definition diagram), and its constituting stages. Each of the life-cycle models is composed by "*stage*" elements (concept from the life-cycle ontology cluster), as defined by the ISO\IEC 15288, and for each stage corresponding processes and interactions within stages are modeled as well.

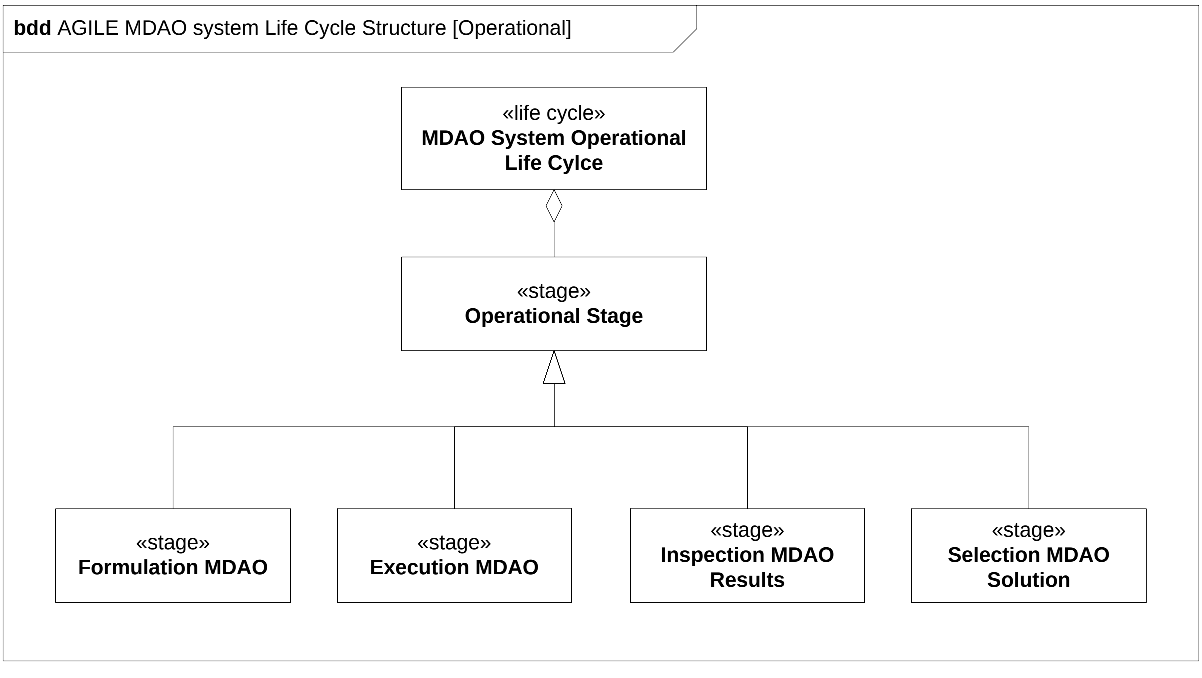

Figure 17 *AGILE MDAO System* – Life-Cycle Structure View: the model of the operational life-cycle is here represented as example. Each "life cycle" is composed by multiple "stage" elements.

The model of each stage contains information of the detailed behaviors within the stage. As example, the behavior of the "Execution MDAO" stage is represented in Figure 18 by one of the views instantiated for the "Life-Cycle Behavior" viewpoint (expressed as simplified SysML sequence diagram), defining the interactions between multiple "processes" (concept from the process ontology cluster) contained in the stage.

- **MDA Unconverged Test**: before operating the actual design and optimization study, a test is performed by executing a so-called Multidisciplinary Design Analysis of the MDAO problem to be solved, consisting in removing every feedback connection between the disciplinary competences (therefore, unconverged). If the test is successful, alternatives studies can be executed, as represented by the other processes.
- **Single Point Analysis**: the MDAO system implemented is operated to perform a single point analysis, therefore an MDA. The optimization driver is not enabled in this case.
- **DOE**: a Design Of Experiment study is performed. This specific sampling schema is configured during the "Formulation MDAO" stage.
- **Optimization**: an optimization study is performed. This specific optimization type is configured during the "Formulation MDAO" stage.

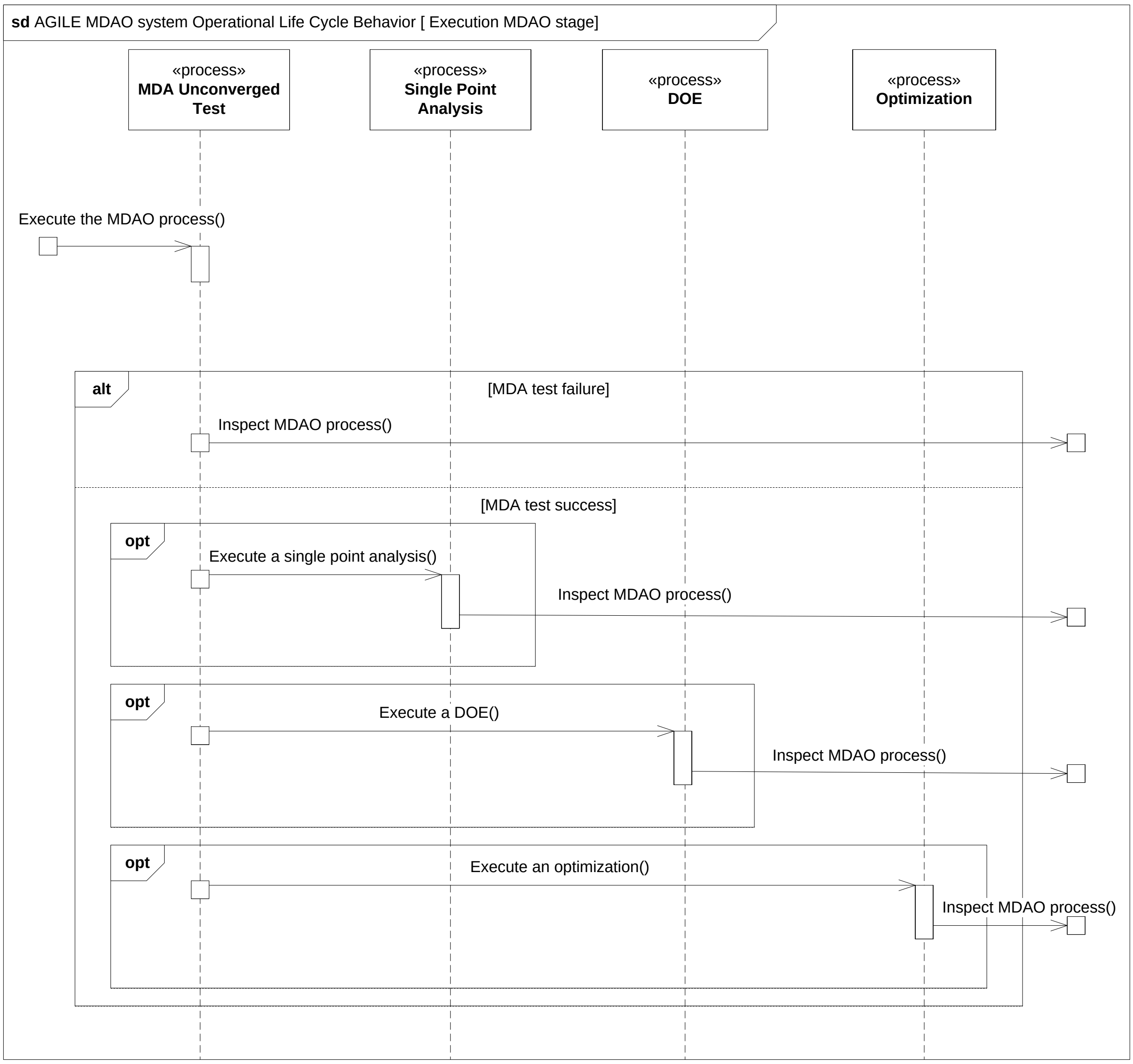

Figure 18 *AGILE MDAO System* – Life-Cycle Behavior View: the model of the interactions between the *process* elements contained in the *stage* "Execution MDAO", which belongs to the "Operational life-cycle" previously presented. A MDA test is performed at first. If successful, alternative studies can be initiated.

The modeling of the life-cycle in the *AGILE MDAO system* is a key to support the decision making, regarding the necessary changes, but also to evaluate the impact of exchanging a certain element of the system, or extending its scope.

4. MDAO design system "Process Perspective"

The *AGILE MDAO system* model includes an extensive list of processes, which are included in all the phases of the life-cycle. Therefore, these cover the deployment of the system, the setup of the optimization problem, the operations of the MDAO system from the multiple stakeholders, etc. The processes characterize and describe the behavioral aspects of the *AGILE MDAO system*. As example, Figure 19 represents one of the views instantiated for the "Process Library" viewpoint (Table 4), for the processes related to on the stages in the "operational life cycle" model (expressed as simplified SysML block definition diagram), and defining its processes (concept from the process ontology cluster).

Each of the process block, contains the detailed list of "activities" and "artifacts" produced\consumed by those activities. Figure 19 represents one of the views for the "Process Artifact", showing such exchange of artifacts related to the process of a "MDAO process". Details on the specific processes retained in the diagrams are out of the scope of this paper.

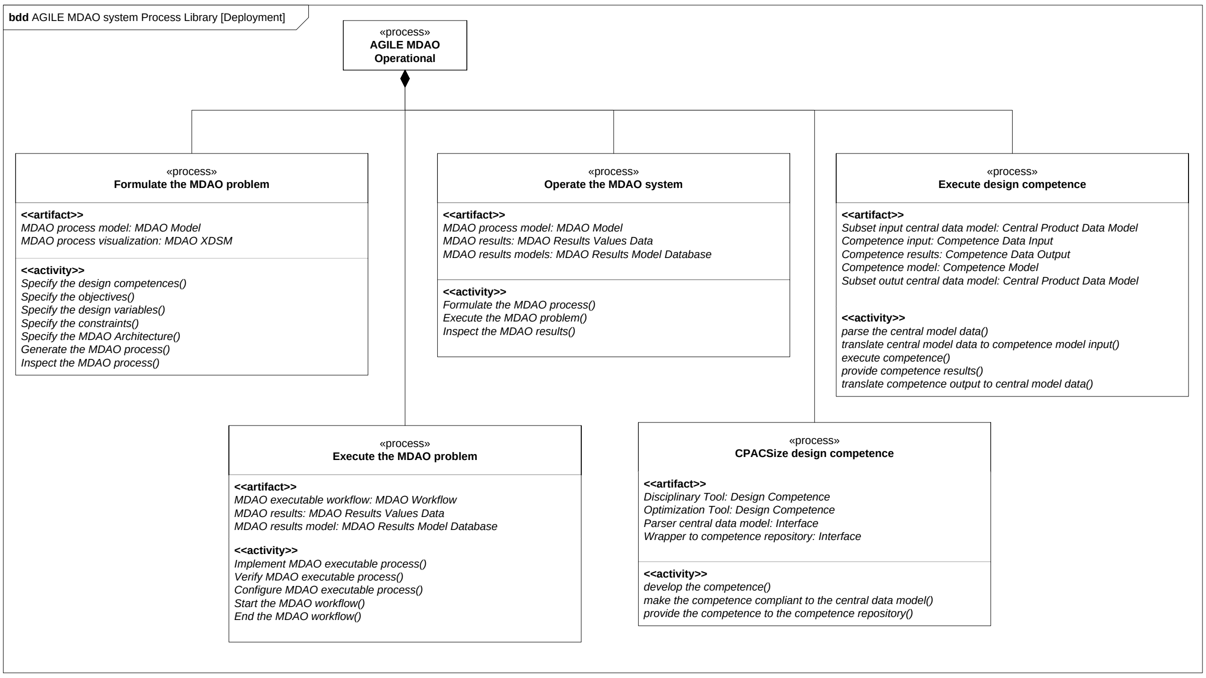

Figure 19 *AGILE MDAO System* – Process Library View: the model collects the processes which are executed during the stages of the life-cycle. In this example a selection of processes has been retained. For each process a series of "activity" and "artifact" are specified.

In the same perspective, the interaction between the artifacts is given by the Artifact interaction viewpoint, as shown in **Figure 20** (expressed as simplified SysML block definition diagram). Such a view can be instantiated for each process, or between processes.

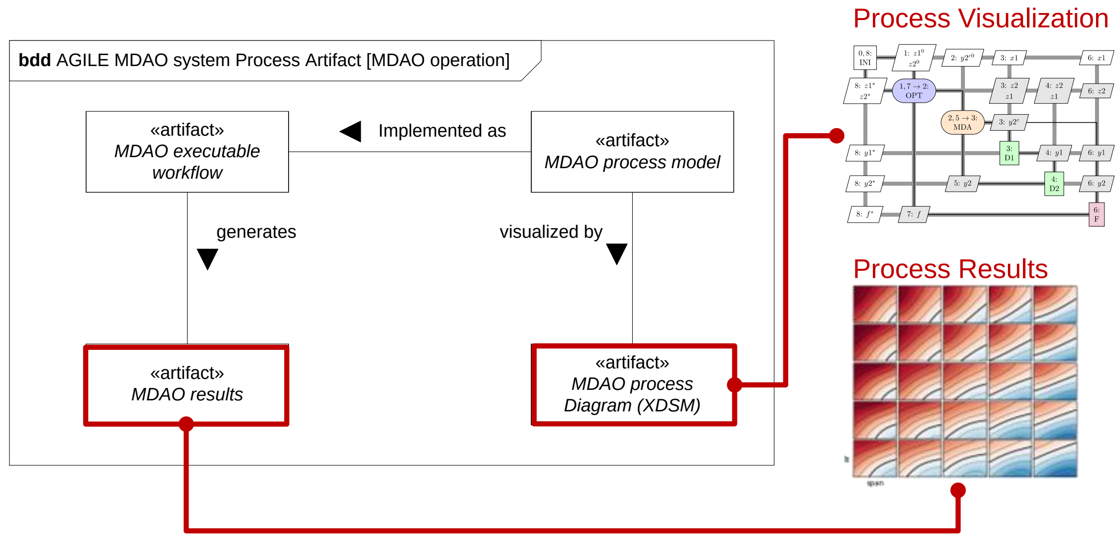

Figure 20 *AGILE MDAO System* – Process Artifact View: the model of the interactions between the artifact produced\consumed by the processes. In this example the artifacts are the ones produced during the operation of the MDAO system.

5. MDAO design system "Requirements Perspective"

The diagram which has been shown in Figure 8, representing the agility needs for the next generation of "design systems", is actually the view of the high level needs for the AGILE MDAO system, from which detailed requirements have been originated.

A "*requirement*" (a concept from the need ontology cluster) can be classified in categories, and expressed according to rules and best practices, as well as it owns properties such as an identifier. Furthermore, once modeled the requirement can be linked to the stakeholders, and to other elements of the model.

An important benefit of modeling the architecture MDAO system is the traceability of the requirements. In particular, these can be traced back to the elements of MDAO system which have been developed, and to the means of verification which have been established.

Figure 21 represents one of the views instantiated for the "Requirement Traceability" viewpoint (Table 2), for a single requirement among the ones defined (represented as simplified SysML requirement diagram). The model enables to trace the connection of the component "Communication Channel" belonging to the *AGILE MDAO system* (as shown previously in Figure 16), which has been developed to satisfy the requirement "Support Cross-Organizational Service". In addition, the way in which the verification is performed is also shown in the traceability view, by the connection with an instantiation of the "test case" (a concept from the need ontology cluster, aligned with the definition by the SysML standard). In this example, such a test case provides a nominal scenario in which a design service (e.g. an aerodynamics analysis) has been effectively executed and provided as a service outside the organizational border. However, multiple test cases have been modeled for other non-nominal, and "what-if" situations. Each requirement of the *AGILE MDAO system* can be traced to corresponding test cases. The full traceability of the model is an essential characteristic to be able to exchange and extend components in the MDAO system, and evaluating the impact along the entire life-cycle.

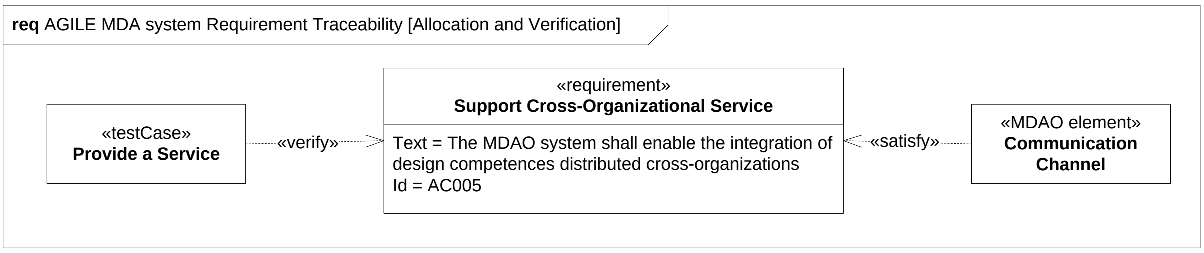

Figure 21 *AGILE MDAO System* – Requirement Traceability View: represents the definition of the requirement and models the connection with corresponding element of the AGILE MDAO system developed (in the example just a single one), and the means of verification, indicated by the "*testCase*" construct, which has been established to verify the requirement.

VIII. Conclusions and Outlook

A. Conclusions

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 developments.

However, the current *design systems* (e.g. MDAO, PLM, KBE, etc.) supporting the product development exhibit a "lack of agility" to be effectively deployed in large-scale programs. 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 acknowledged advantages, are not yet fully exploited outside of the research programs.

In MDAO systems, the efficiency increases are often sought in the performance of the optimization algorithms, or the disciplinary analysis. In this context, the authors have previously formulated the ***AGILE Paradigm***, which introduces 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). However, although the *AGILE Paradigm* approach has proved to drastically reduce the development time of aircraft products, it has **not been formalized and modeled** by leveraging digital design engineering practices.

In product development context, Model Based Systems Engineering (MBSE) and Multidisciplinary Design Analysis Optimization (MDAO) are both aiming at supporting the development of complex systems.

Therefore, the work here presented proposes to leverage MBSE principles to streamline the development of *MDAO design systems* supporting the design of complex aeronautical products, and establishing for the first time **a bridge between MBSE and MDAO approaches**. Specifically, this work leverages MBSE-driven approaches for the development of *AGILE MDAO design systems*, modeling and formalizing the informal principles envisioned by the *AGILE Paradigm*, and therefore removing the aforementioned limitations.

The major outcomes of the developed approach, presented in this paper and summarized in Figure 22, are twofold:

1. The MBSE model of the so-called ***AGILE MDAO system***: defines, formalizes and models the architecture of the MDAO systems, which can be efficiently deployed to support and accelerate the development of complex products in large-scale, cross-organizational, distributed programs (therefore, satisfying the agility need). The resulting model is described by multiple views, focusing on dedicated aspects of the MDAO system, many of which never formalized before. Only a selection of high level views is presented in this paper.

2. The MBSE model of the so-called ***AGILE Architectural Framework***: defines the approach supporting the model based definition, and guiding the development of the *AGILE MDAO system*. Such a framework defines the rules and rationale to instantiate views and perspective of the *AGILE MDAO system*, and establishes the underlying ontological concepts which are needed for modeling the architecture of the *AGILE MDAO system*. Also for the *AGILE Architectural Framework*, only a limited selection of the high-level model elements is presented in this paper.

As shown in the paper, all the ontology elements and all the views instantiated are connected to each other, and form the architectural model of the *AGILE MDAO system*.

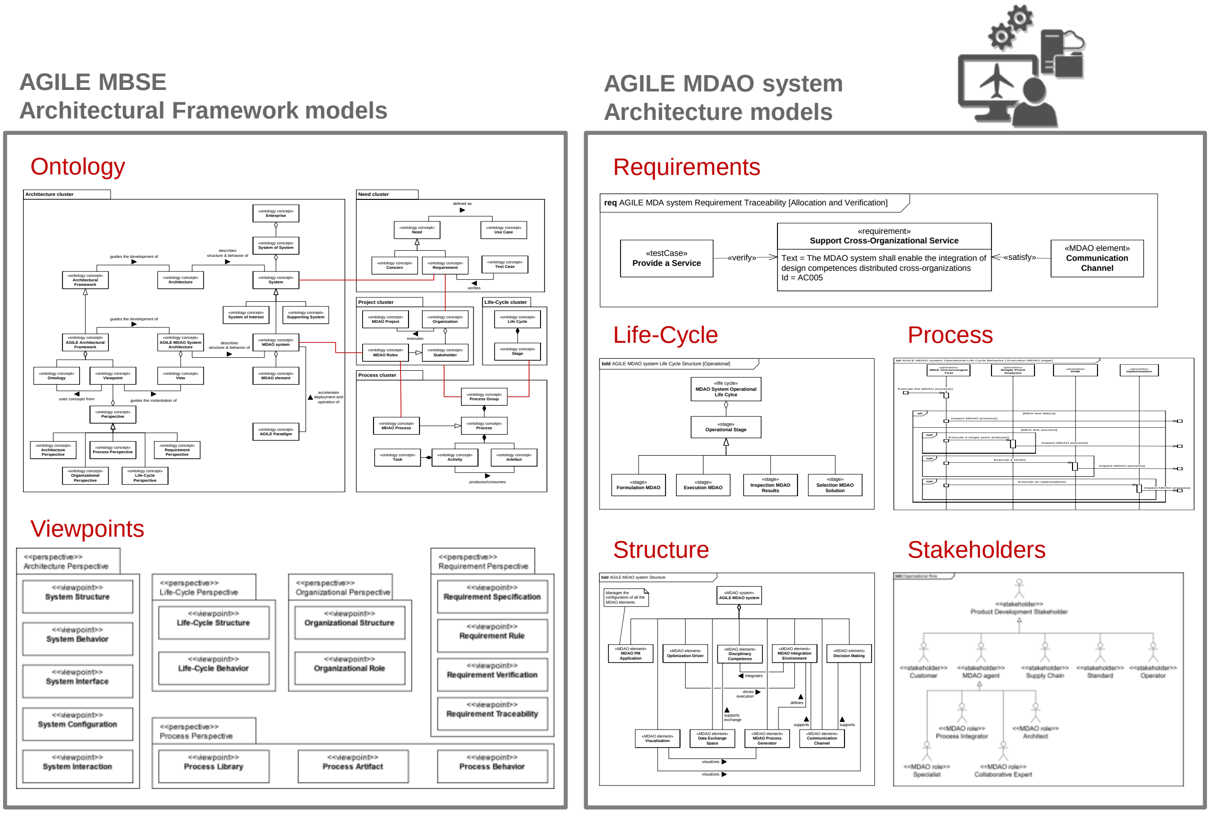

Figure 22 AGILE MBSE Approach to MDAO systems.

The **value of an MBSE-driven approach for the development of *AGILE MDAO system*** is in the formalization and modeling of the *AGILE Paradigm*, an approach which has proven to increase the efficiency of the deployment and operation of complex MDAO design systems, accelerating the development of aircraft products. Although successful, the *AGILE Paradigm* was not formalized during the AGILE project, which challenged the implementation of the approach outside the project context. The formalization step here presented, driven by MBSE principles, will enable the further exploitation of the approach.

Furthermore, the modeling of the architecture of the *AGILE MDAO system* enhances the transparency in understanding the logics and functionalities of such agile MDAO system, before any implementation takes place. In addition the model of the *AGILE MDAO system* can be queried, for instance to check the consistency of the envisioned flow of information between computational elements of the design system itself, or between stakeholders engaged with operating the MDAO system, before processes are actually executed during in the development. Furthermore, the model of the *AGILE MDAO system* can be executed to investigate “what-if” scenarios, such as assessing the impact in case a specific element of the design system is not implemented in time, or it has to be replaced by an alternative one. Finally, such a model provides the core to support the expansion in scope of the *design system* to the entire life-cycle of the product under development, as already discussed.

Only a selection of the high level model’s elements is presented in this paper, and represented by making use of the SysML standard, in order to facilitate the communication of the models via a human-readable representation. As discussed in previous sections it is not in the scope of this paper to present all the details of the model, but rather to introduce the overall novel approach, and those high-level model’s elements useful for the understanding of approach. It is planned to published and release a detailed model afterwards in an appropriate format.

In summary the paper addresses the following objectives:

- Presenting the current challenges for the development of complex systems (Section III).
- Introducing the overview of the "*model based conceptual framework*" for architecting, designing and optimizing complex aeronautical systems (Section IV).
- Identifying the current gaps to enable the next generation of "*design systems*", with focus on MDAO (Section V).
- Presenting a novel MBSE approach to the development of agile MDAO systems, and the major outcomes of such approach: the aforementioned "*AGILE Architectural Framework*" (Section VI) and the "*AGILE MDAO system*" (Section VII).

B. Outlook: AGILE4.0 Project

After the conclusion of the AGILE project (2015-2018), a follow-up European Commission funded project has been recently launched: AGILE4.0 (2019-2022) [21]. The high level objective 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. AGILE4.0 will provide the aircraft industry with a way to model, assess, and optimize complex systems addressing the entire life-cycle. The technologies developed will enable the stake-holders and actors of the aeronautical supply chain to **perform trade-off which are rarely modeled today**. To meet this challenge a Consortium of 18 industry, research and academia partners from Europe, Canada, Brazil, and Russia are collaborating together.

Therefore, the MBSE approach to MDAO design systems presented in this work provides **the core formalization and modeling elements of AGILE4.0 project, and it will be extended to cover the entire life-cycle**.

Acknowledgements

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