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THE AGILE 4.0 MBSE-MDAO DEVELOPMENT FRAMEWORK: OVERVIEW AND ASSESSMENT

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Abstract

The EU-funded H2020 AGILE 4.0 project targets the enhancement and acceleration of processes for the development of complex aeronautical systems throughout multiple life-cycle stages, including design, production, certification and maintenance. In order to reach this ambition, the project Consortium has developed an original methodology and innovative digital technologies in the context of Model-Based Systems Engineering (MBSE) and Multidisciplinary Design Analysis and Optimization (MDAO). The methodology and the technologies are part of the AGILE 4.0 MBSE-MDAO Development Framework. This paper aims at presenting an overview of this framework, and assess its efficacy, i.e. demonstrate that the proposed framework improves the current state-of-the-art. Therefore, assessment metrics are identified and used to quantify how much the proposed methodology and digital technologies can effectively accelerate and enhance the development process of complex aeronautical systems.

Keywords: Systems Engineering, Model Based Systems Engineering; Multidisciplinary Design, Analysis and Optimization; EU-H2020 AGILE 4.0 project; Assessment metrics

1. Introduction

The aviation sector is facing for the next decades strong challenges as climate neutrality, sustainability and the ever-increasing demand of higher performance. These challenges are pushing aeronautical industries and research centers to develop radical innovative concepts characterized by novel and disruptive technologies. These technologies include for example innovative propulsion systems (e.g. hybrid-electric and hydrogen-powered systems), more efficient high-aspect ratio laminar wings, more electric on-board systems, new materials.

The introduction of new technologies and the identification of innovative solutions inevitably increase the complexity of the development process of a new system, as an aircraft or part of it (e.g. an engine). This complexity is also intensified by the enlargement of the whole aeronautical supply chain, where more and more organizations with different people, skills and nationality, are called to take part in the same program. Moreover, the duration of the system design, from its concept to its realization, certification and delivery, is increasing, therefore jeopardizing the success of the system in the competitive market.

For these reasons, the multi-organization development process of complex innovative systems needs to be streamlined and accelerated, across all the different disciplines, and throughout its entire life-cycle. This improvement and acceleration of systems development process cannot happen without the formulation and implementation of new development methodologies, which should leverage digital design engineering principles to effectively and rapidly combine people, expertise and technologies within a collaborative, multi-national and cross-organizational context. In other words, the implementation of new disruptive technologies should entail the development of tools, processes and methods that enable their timely, on quality and on cost integration on a development program.

The H2020 AGILE 4.0 project (2019 - 2022) funded by the European Commission (EC) [1] aims at overcoming the system development challenges previously introduced by leveraging new model-based approaches. The AGILE 4.0 project extends the scope of the previous EC-funded H2020 AGILE project (2015 - 2018) [2], which aimed at improving, streamlining and accelerating the formulation, deployment and execution of cross-organizational Multidisciplinary Design Analysis and Optimization (MDAO) processes [3]. The new scope extended by the new project includes Systems Engineering activities (such as requirement engineering and architecture generation and trade-off). Such activities are recommended by various entities – among all, the International Council on Systems Engineering or INCOSE [4] – that promote initiatives, research and developments aiming at successfully handling the “perceived complexity” of innovative systems. Therefore, the ambition of the AGILE4.0 project is the reduction of aircraft development costs and time-to-market throughout the implementation of an integrated aeronautical supply chain, from integrators and high-tiers suppliers to SMEs, which would lead to innovative and more sustainable aeronautical products. In particular, AGILE 4.0 targets the digital transformation of main pillars of the aeronautical supply-chain, including design, production, certification and maintenance. A project Consortium of 16 European and extra-European partners (i.e. from Canada and Brazil) from research, academia and industry is collaborating for the achievement of the just mentioned ambition [3]. A representation of the project Consortium and the main pillars addressed in AGILE 4.0 is given in Figure 1.

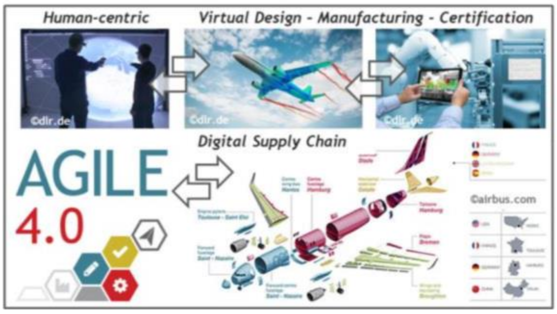

Figure 1 – The AGILE 4.0 project Consortium (left) and the main aeronautical pillars addressed in the project through the development and application of new digital technologies (right) (adapted from [3]).

2. The AGILE 4.0 MBSE-MDAO Development Framework

In order to reach the ambition introduced in the previous Section, the AGILE 4.0 project Consortium is building a new development framework that consists of methodologies and digital technologies that support the development of aeronautical systems. The AGILE 4.0 development framework exploits model-based approaches, due to their potential benefits in terms of easier design activities, enhanced design quality, better system specification and improved communications within the design team [5]. In fact, models can effectively support, improve and accelerate all the activities of a Systems Engineering Product Development process, such as definition of customer needs, identification of system functionalities, collection of requirements, generation of alternative system architectures and verification and validation tasks. Therefore, all these motivations have given great popularity in the last decade to Model Based Systems Engineering (MBSE), which is expected to play an increasing role in the field of Systems Engineering in the next decades [6]. In addition, the AGILE 4.0 development framework targets to bridge MBSE and MDAO activities ([3], [7]). Indeed, the AGILE 4.0 MBSE-MDAO Development Framework focuses on connecting two phases of the complex system development process (see Figure 2):

1. **“upstream architecting” phase**, which includes the main activities of a typical (document or model-based) Systems Engineering Product Development process: identification and trade-off of goals and capabilities that the system needs to deliver, the specification of operational scenarios and requirements accounting for all the stakeholders involved and their expectations, and the design and optimization of the various and alternative architectures (different configurations) of the system;
2. **“downstream product design and optimization” phase**, which aims at identifying and selecting the disciplinary competence (e.g. aerodynamics), formulating and executing MDAO processes and exploring and assessing the solutions space.

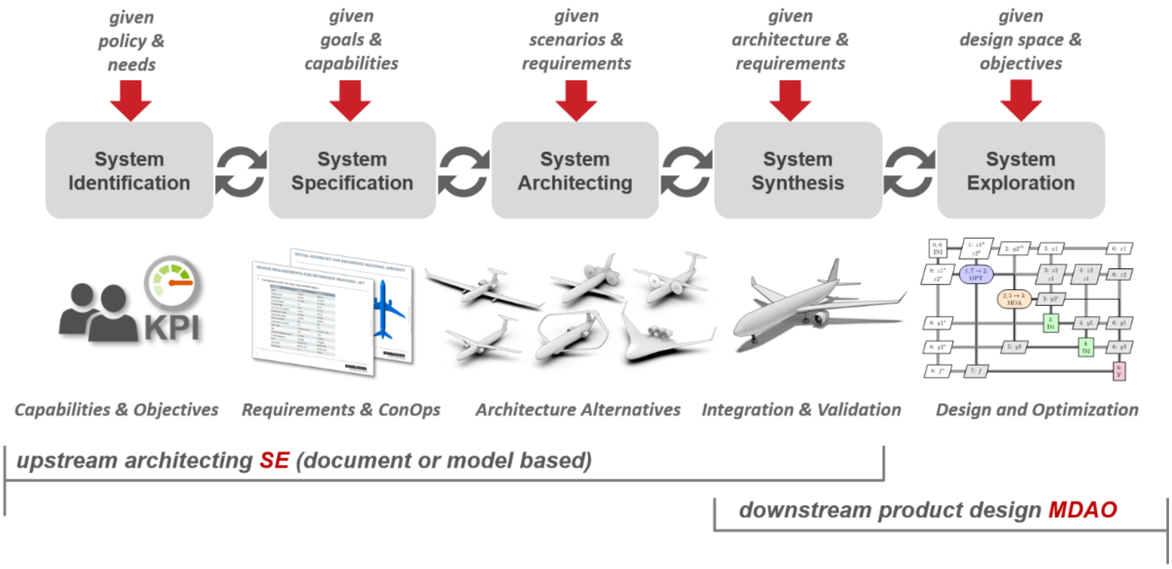

Figure 2 – The AGILE 4.0 MBSE-MDAO Development Framework: "upstream architecting SE" and "downstream product design MDAO" phases (adapted from [3]**)**.

The AGILE 4.0 MBSE-MDAO Development Framework consists of a new model-based methodology developed by the DLR Institute of Systems Architecture in Aeronautics. The methodology provides guidelines supporting the definition and modeling of the main artifacts produced with the AGILE 4.0 Systems Engineering approach, e.g. requirements, system architectures, MDAO formulations. These guidelines include:

- **Processes**, i.e. the sequences of activities necessary to reach a target, e.g. the generation of system requirements based on the stakeholder needs.
- **Ontologies**, i.e. the definitions of all the key concepts (e.g. need, requirement, architecture, MDAO) that are addressed during the development, and relationships between them. These key concepts are represented in different representations – named views – of the system being designed [8].
- **Viewpoints**, i.e. the conventions for the construction, interpretation and use of system views from the point of view of specific system concerns, named perspectives [8].

All the guidelines of the AGILE 4.0 MBSE-MDAO Development Framework are described in details in different publications, each one focusing on a specific scope: System Identification and Specification [9], System Architecting and Synthesis [10] and System Design and Optimization [11].
In addition, the AGILE 4.0 project is realizing an implementation of the development framework, by identifying existing software or developing new tools, and integrating them together within a single MBSE-MDAO Development System, which is called Operational Collaborative Environment (OCE), and whose realization is coordinated by KE-works.
This paper aims at presenting an overview of the AGILE 4.0 MBSE-MDAO Development Framework and its assessment. Section 3 provides an overview of the process for the development and assessment of the framework, while more detailed explanations about the technologies of the framework are provided in Section 4. Section 5 reports and describes the assessment results obtained through effectiveness metrics, while conclusions are collected in Section 6.

3. The process for the development and assessment of the AGILE 4.0 framework

The realization of the AGILE 4.0 MBSE-MDAO Development Framework, including its implementation, is done according to the process represented in the diagram of Figure 3.
In particular, this representation shows a Sequence Diagram built according to the standard modelling language SysML [12], extensively adopted in MBSE [13]. The realization and assessment of the framework includes the following main activities:

1. Definition of the needs and requirements of the framework;
2. Development of the framework and implementation into the OCE;
3. Assessment of the framework, in order to evaluate its performance and efficiency.

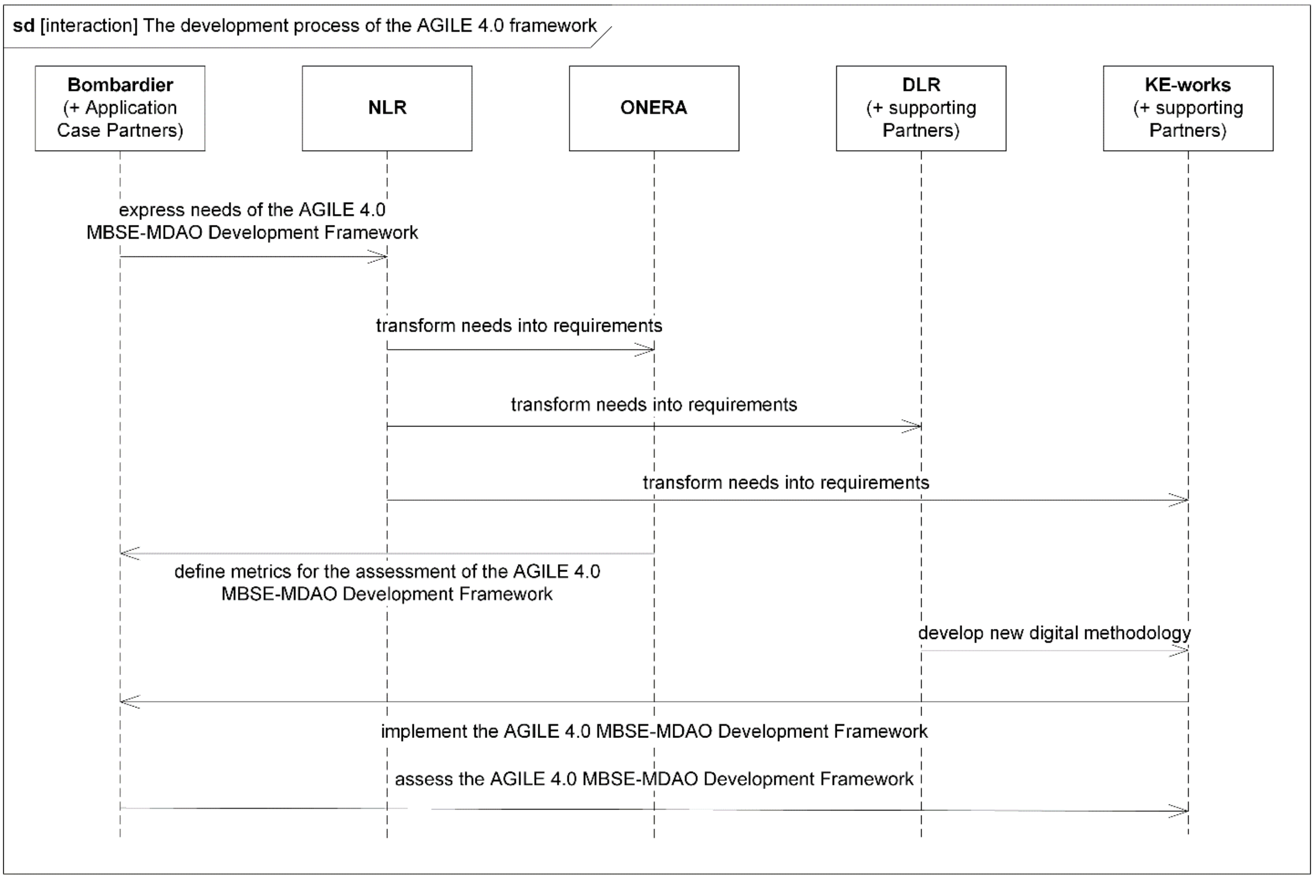

Figure 3 – SysML Sequence Diagram representing the process adopted in the AGILE 4.0 project to develop and assess the MBSE-MDAO Development Framework.

The diagram shows the main project partners (authors of the present paper) involved in and/or coordinating the three activities just mentioned. However, contributions and support are given by the entire Consortium.

The process for the realization of the AGILE 4.0 framework starts with the identification of the capabilities that the framework itself should fulfil, and the characteristics that it should have. These capabilities and characteristics are expressed as needs from the framework, and they are collected from the project stakeholders, which encompass the industrial partner Bombardier and the Application Case partners, i.e. the users of the Development Framework for the conceptual design of different aircraft and aeronautical systems defined in the project as representative case studies. Different is indeed the role of Bombardier and the Application Case partners for the definition of the needs and expectations. In fact, Bombardier expresses – thanks to its expertise – the needs related to the MBSE and MDAO capabilities that the AGILE 4.0 Development Framework should have. Instead, the Application Case partners mainly demand needs relative to the simulation and disciplinary capabilities that are required to design (an often optimize) the different case studies targeted in the project.

The expressed needs about the development framework are then transformed into technical requirements. Differently from needs, requirements follow predetermined structures and guidelines, which assure important qualities to the requirements, as completeness, correctness, and unambiguity. This task is performed by NLR through a document-based approach, since requirements are collected and managed through excel tables. However, a requirements model is also created, and part of it is represented in the SysML Requirements Diagram Figure 4 (adapted from [9]). An example of requirement is *the AGILE 4.0 MBSE-MDAO Development Framework shall support the traceability between all the elements of the model* (requirement MBSE.10). This framework requirement is important to assure that each system (e.g. aircraft) requirement is linked to a source, i.e. it is generated from another requirement or from a stakeholder need. In this way, it is formalized and clear the origin of the requirements. Similarly, all the designed solutions and decisions have to be traced back to the requirements, for verification purposes. The collected requirements drive the development of the AGILE4.0 MBSE-MDAO Development Framework and its implementation (i.e. the OCE).

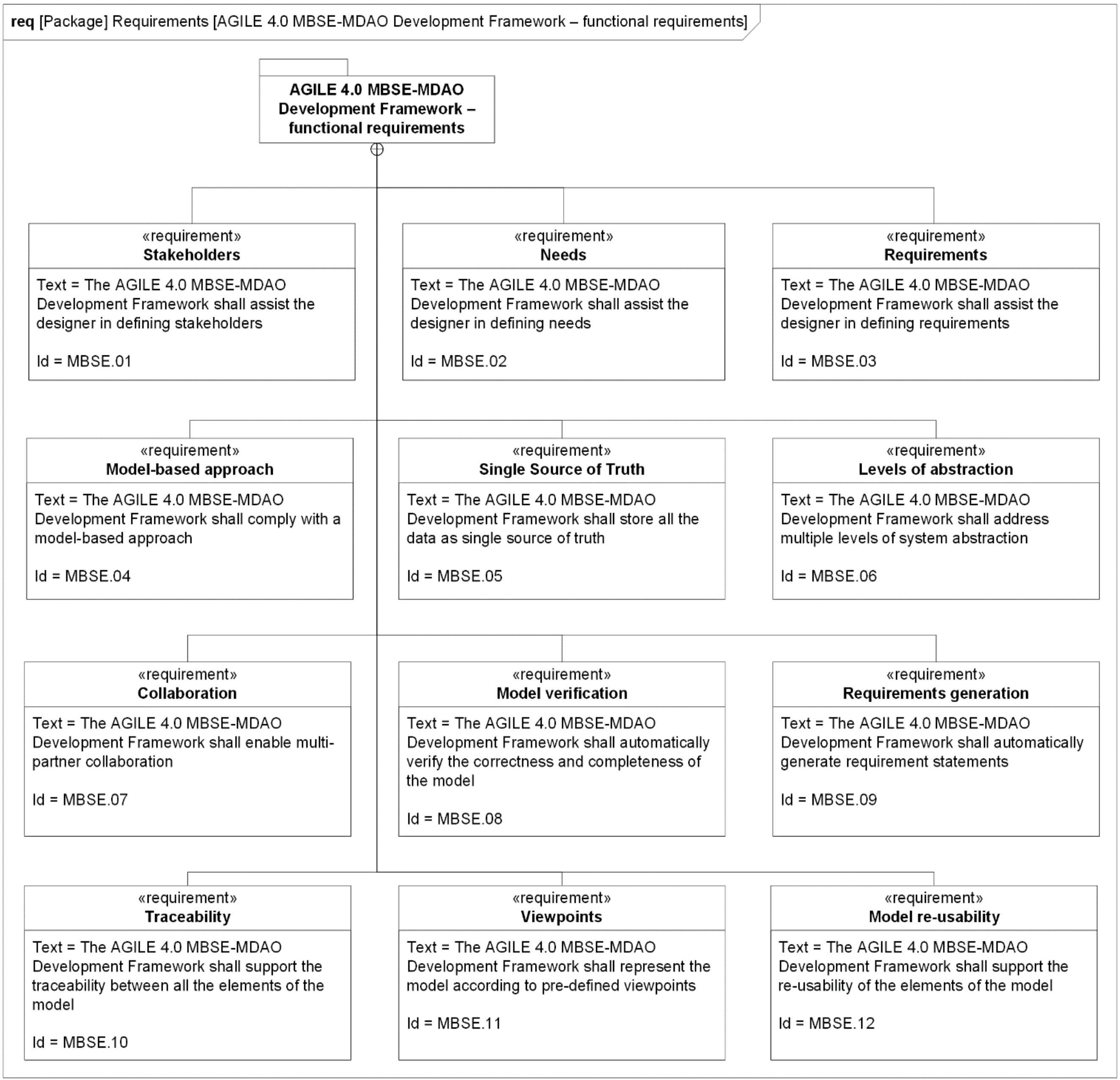

Figure 4 – SysML Requirements Diagram representing part of the requirements of the AGILE 4.0 MBSE-MDAO Development Framework (adapted from [9]).

In addition, assessment metrics – called ***Framework Effectiveness metrics*** – are extracted from the requirements by ONERA. The purpose of these metrics is the evaluation about if and how well the methodologies and digital technologies developed in the AGILE 4.0 project and part of the development framework support the design of Application Cases and reflect the expectations of the industrial partner Bombardier. The evaluation through the metrics is done for all the activities performed in the downstream and upstream phases of Figure 2.Three effectiveness metrics are identified in the project:

- **Time** necessary for each Application Case to perform each one of the AGILE 4.0 activities;
- **Easiness** of performing the five AGILE 4.0 activities by means of the development framework";
- **Completeness** of the planned activities thanks to the methodology and technology developed in the project.

The assessment of the AGILE 4.0 MBSE-MDAO Development Framework through the metrics is performed to judge the "quality" of the developed methodology and technology and – when possible – to adopt countermeasures in order to make all the necessary improvements.

4. Overview of the technologies of the AGILE 4.0 framework

The methodology of the AGILE 4.0 MBSE-MDO Development Framework developed in the project is implemented into multiple digital technologies (i.e. tools) that are part of the OCE. These technologies support the development activities of the Systems Engineering approach addressed in the project, from the identification of system stakeholders to the execution of MDAO workflows. All these activities are formalized by the processes described in [9] (definition and modelling of stakeholders, needs, scenarios and requirements), in [10] (system architecting and modeling) and in [14] (MDAO formulation and execution). Moreover, multiple views are generated through the OCE and in conformity with the viewpoints prescribed by the AGILE 4.0 framework. These views allow the system designers to visualize all the information (e.g. requirements, architectures) of the system under design.
An overview of all the technologies of the OCE is provided in [15], and a graphic representation of them is given in Figure 5.

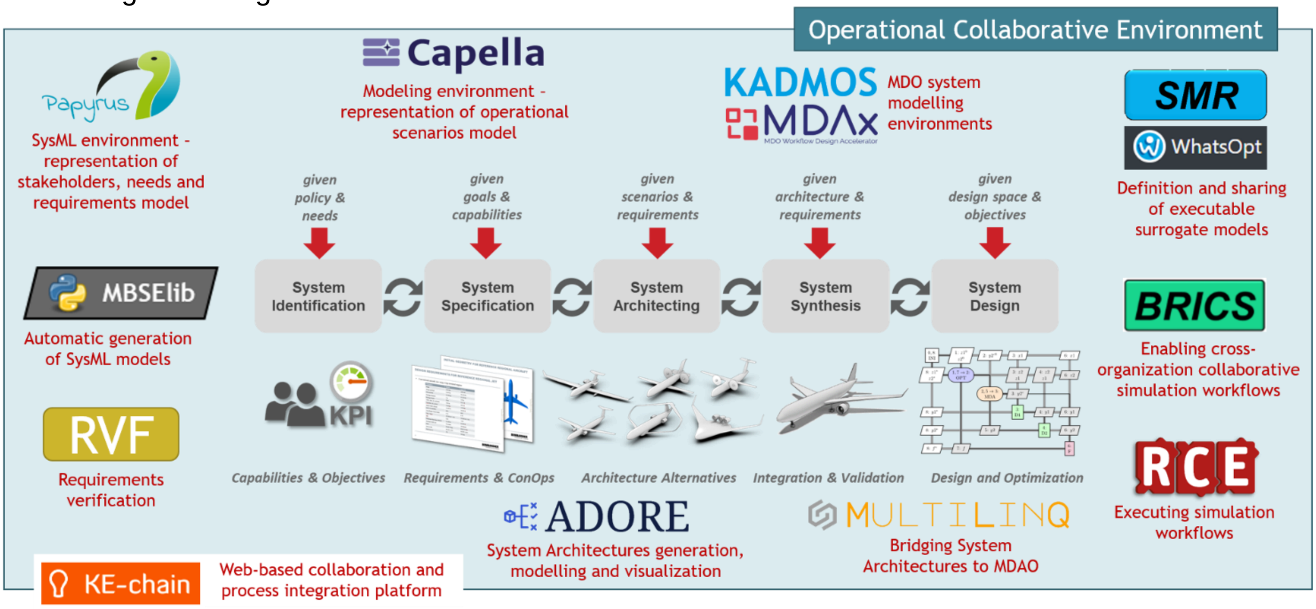

Figure 5 – Schema with the overview of the technologies of the AGILE 4.0 MBSE-MDO Development Framework. The implementation of the framework is named Operational Collaborative Environment (OCE).

The web-based collaboration and process integration platform *KE-chain*[1] connects all the technologies together into a single development process, and includes user interfaces to define some inputs required from the designers, e.g. requirements and system functions. Some of the inputs provided to KE-chain, specifically stakeholder, needs and requirements, are used by the tool *MBSElib* to automatically generate SysML models that can be used by the system designer for inspection purposes [9]. These models are built according to the viewpoints of the AGILE 4.0 framework, and they can be visualized in the *Eclipse Papyrus*[2] environment. The open-source *Capella* tool[3] instead is used in AGILE 4.0 to model operational scenarios. Multiple system architectures can be then generated, modelled and visualized in *ADORE* [16]. Design disciplines for the MDAO problem are consequently derived in order to design and optimize one or more system architectures, and in compliancy with all the defined requirements. Therefore, the *Requirements Verification Framework (RVF)* [17] and the *MultiLinQ* tool [7] are integrated in the OCE in order to support the designers in defining which disciplines are needed to verify the requirements and to address the generated architectures. Two other technologies are then employed for the formulation of the MDAO workflows: *KADMOS* [18] and *MDAx* [19]. The formulated workflows are then imported in the *RCE* environment[4], where they are executed. These workflows include disciplinary tools, or executable surrogate models, which are made available through *WhatsOpt* [20] and the *Surrogate Model Repository (SMR)* [21]. Since all the tools and models are owned by different partners and located in different locations, and in order to protect the Intellectual Property of each disciplinary

[1] https://ke-chain.com/en/
[2] https://www.eclipse.org/papyrus/
[3] https://www.eclipse.org/capella/
[4] https://rcenvironment.de/

expert, the *BRICS* technology [22] is employed, hence enabling the execution of cross-organization collaborative simulation workflows.

The technologies of the OCE are then exploited by the Application Cases addressed in the AGILE 4.0 project. The assessment of these technologies is done by the Application Case partners and the industrial partner Bombardier through the evaluation of the identified effectiveness metrics, as explained in the following Section.

5. Assessment of the AGILE 4.0 MBSE-MDAO Development Framework

The requirements and metrics introduced in Section 3 are now used for the assessment of the AGILE 4.0 MBSE-MDAO Development Framework. In other words, the resulting framework is first verified against the listed requirements. Requirements that are not satisfied by the solution represent some gaps that the AGILE 4.0 project might still not be able to fill. On the contrary, requirements that are satisfied represent the “goodness” of the project achievements. Then, the assessment is performed through the interpretation and discussion of the metrics. Again, the results of the assessment can be used to identify where additional research, maybe in a different project or context, should be carried on.

In total 109 requirements of the AGILE 4.0 MBSE-MDAO Development Framework have been derived from the needs expressed by Bombardier. 51 requirements prescribe the functionalities and the performance of the technologies supporting the activities of the “upstream architecting” phase represented in Figure 2. 58 requirements are instead addressing the MDAO activities of Figure 2. Among all these requirements, only few of them are not verified by the AGILE 4.0 technologies. In particular, the technologies integrated into the AGILE 4.0 MBSE-MDAO Development Framework don’t allow to model the following elements:

- the **mission** to be performed by the system of interest;
- the **interdependencies between functions**;
- the **interfaces** between components.

However, it should be noted that many tools (also available as open source, as Eclipse Capella) can be easily used by aeronautical designers to define and model these missing elements, and the obtained information can be effectively integrated in the AGILE 4.0 framework.

As introduced before, three effectiveness metrics are used to evaluate the developed technologies supporting the activities during the downstream and upstream phases of Figure 2: time, easiness and completeness. This section presents some of the main assessment results obtained during the evaluation of the AGILE 4.0 MBSE-MDAO Development Framework. The assessment has been done by comparing the technologies of the framework with those of the state-of-the-art, with respect to each single development activity of the Systems Engineering Product Development Process, e.g. collection of requirements and generation of system architectures. A score between “worse” and “better” has been assigned by the designers of each one of seven Application Cases addressed in the AGILE 4.0 project. For example, the diagram of Figure 6 shows the assessment of the activity “*Define stakeholders and needs*” of the “*Identification*” step of Figure 2.

Partly discordant results are obtained in the assessment of the technologies for the definition of stakeholders and needs. For only two Application Cases, the developed technologies improve the level of completeness of this activity. Regarding the *time* metric instead, the majority of Application Cases finds an improvement compared to state-of-the-art. Only one of the Application Cases instead points out a slight worsening in terms of the required time for the activity. This is because the developed technologies are characterized by a “learning curve” that demands additional time before the technologies can be effectively exploited. For the same reason, the easiness level is also reduced for one of the Application Cases, while for the other ones, the developed technologies require similar of less effort.

Different is instead the evaluation regarding the activity “*validation of stakeholders and needs*”, where the developed technologies almost always improve the three metrics, as represented in Figure 7. This is because the model generated by the technologies can be automatically “interrogated”, hence identify development errors.

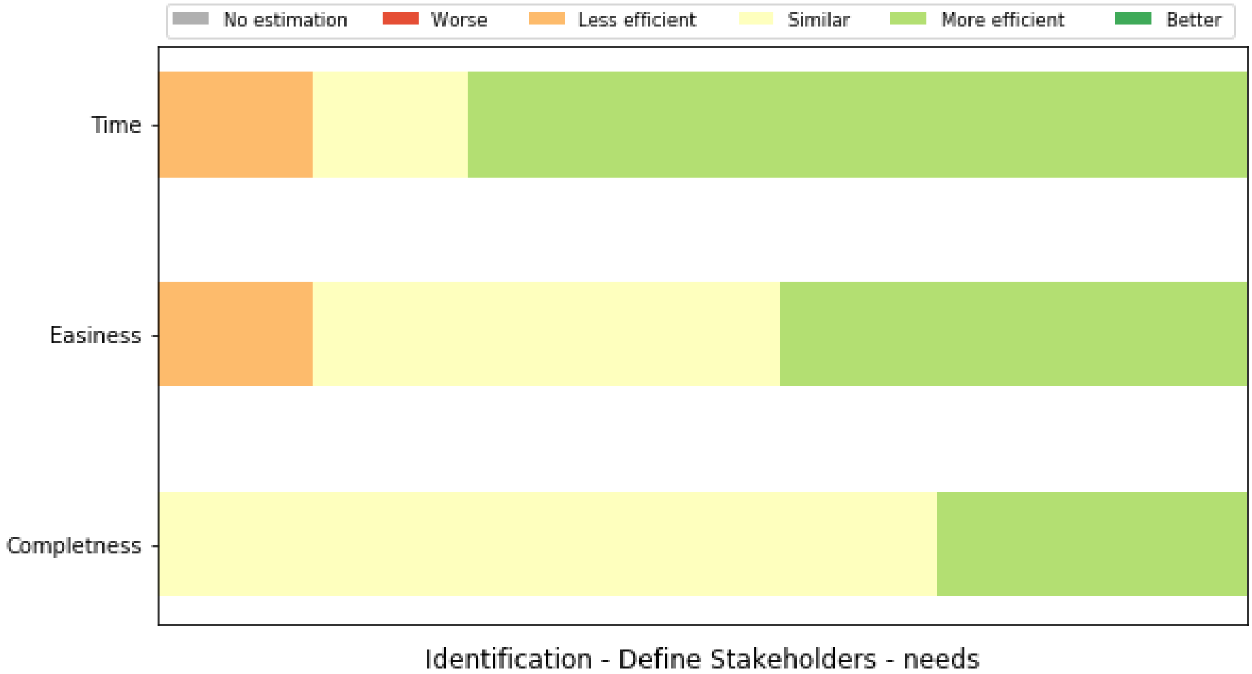

Figure 6 – Framework Effectiveness metrics for the assessment of the Development Framework technologies supporting the activity “define stakeholders and needs”.

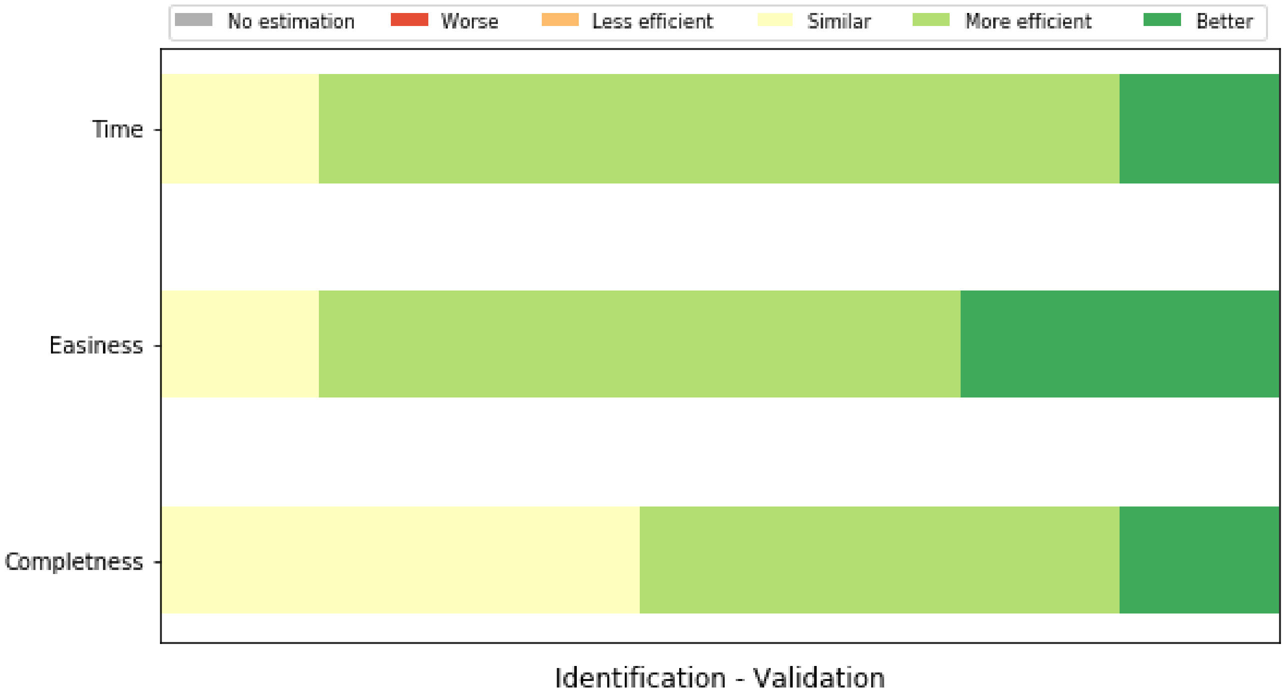

Figure 7 – Framework Effectiveness metrics for the assessment of the Development Framework technologies supporting the activity “stakeholders and needs validation”.

Similarly, the activities related to the requirements engineering (i.e. definition, modeling, visualization, inspection and verification of requirements) are evaluated. In this case, the technologies of the AGILE 4.0 MBSE-MDAO Development Framework seem to bring significant improvements, as shown in the two diagrams of Figure 8.

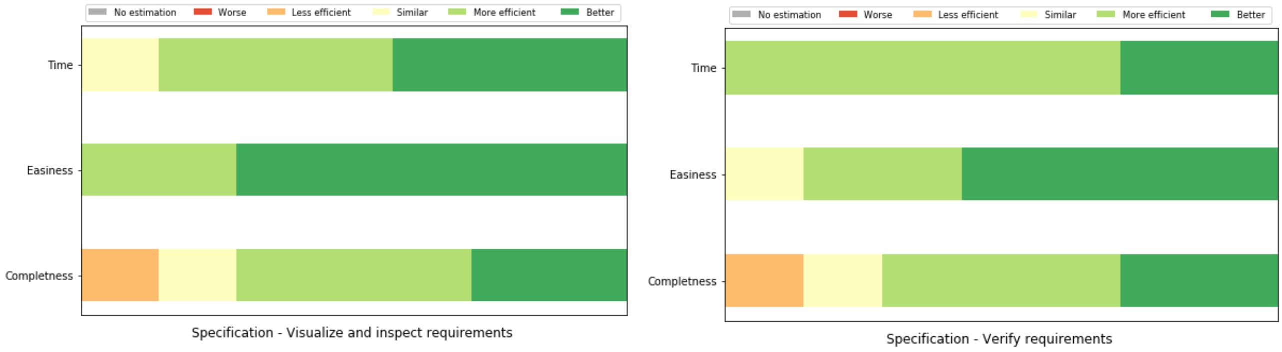

Figure 8 – Framework Effectiveness metrics for the assessment of the Development Framework technologies supporting the requirements engineering activities.

A new system architecting process has been developed and used in the AGILE 4.0 project (see [10] for more details). Therefore, additional activities have been introduced in the development process, as the modeling of the system architecture design space. Inevitably, the development time has increased, as shown in the left diagram of Figure 9. On the contrary, the easiness and completeness of this activity have been improved thanks to the newly developed technologies. In addition, innovate technologies have been developed in the project for the visualization of architecture instances in the architectural design space, hence improving all the three metrics (see right diagram of Figure 9).

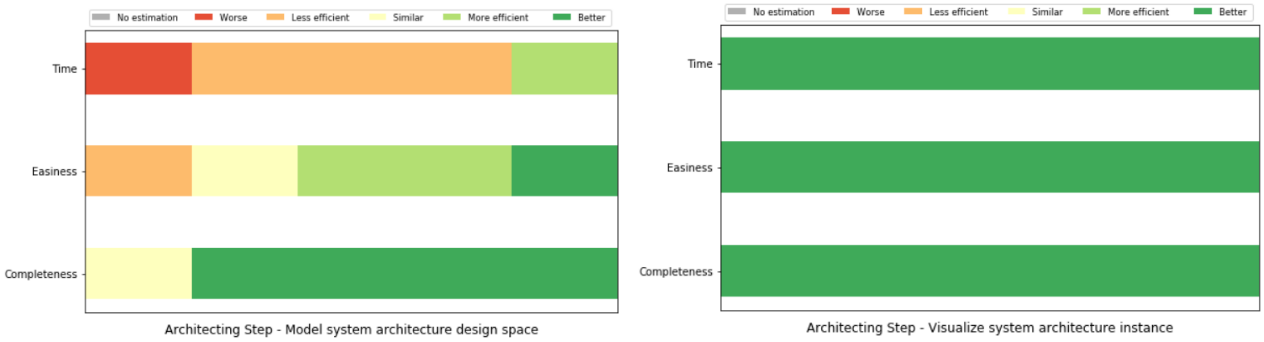

Figure 9 – Framework Effectiveness metrics for the assessment of the Development Framework technologies supporting system architecting activities.

The two diagrams in Figure 10 show instead the effectiveness metrics related to the "*design and optimization*" step. These metrics are evaluated mainly by comparing the changes of the AGILE 4.0 framework with the one developed in the previous AGILE research project. Again, conflicting results are obtained, due to two main aspects. From one side, technologies supporting MDAO activities have been improved from last project, therefore positively affecting the metrics. On the other side instead, more complex workflows including additional constraints and modules from the production, certification and maintenance domains are being formulated and executed in AGILE 4.0, with a consequent downgrade of the metrics.

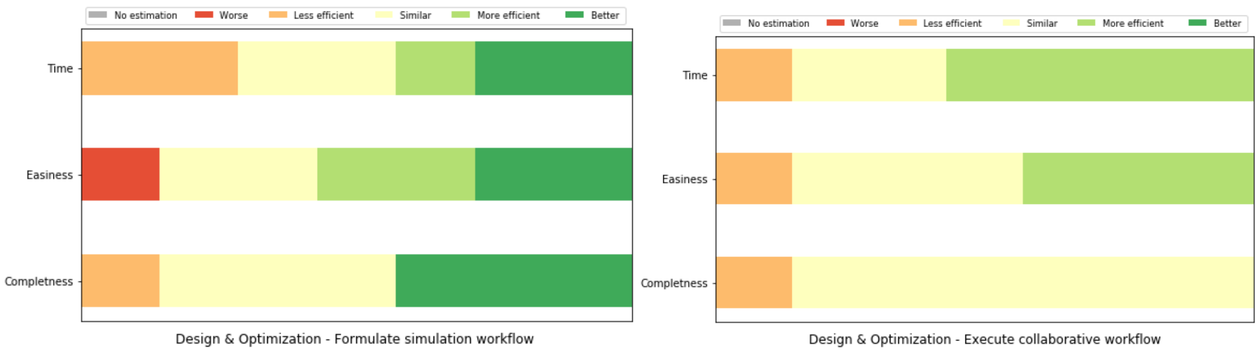

Figure 10 – Framework Effectiveness metrics for the assessment of the Development Framework technologies supporting design and optimization activities.

In conclusion of this Section, it can be stated from the analysis of the resulting effectiveness metrics, that significant improvements have been brought by the AGILE 4.0 MBSE-MDAO Development Framework, especially regarding the new upstream architecting Systems Engineering activities (see Figure 2). Regarding the downstream product design MDAO activities instead, the starting AGILE framework was already quite advance, and therefore no additional and significant improvements have been brought with the AGILE 4.0 project. In general, improvements in terms of completeness of activities of a Systems Engineering Product Development process have been addressed in the AGILE 4.0 framework. In addition, the developed technologies facilitate all the tasks that designers have to perform. However, time required to address each development activity might negatively affected by the inexperience of technology users, but it can be shortened once the users get more experience with development framework.

6. Conclusions

A new methodology and novel digital technologies supporting, improving and accelerating the development of complex aeronautical systems has been developed within the frame of the EU-funded H2020 AGILE 4.0 project. This methodology and technologies are part of the AGILE 4.0 MBSE-MDAO Development Framework. Numerous publications prepared by the project partners address all the parts of the methodology, the different digital technologies, and their application. The present paper instead aimed at providing an holistic overview of the entire framework. In addition, effectiveness metrics for the evaluation of the methodology and technologies developed in the project have been identified. The AGILE 4.0 MBSE-MDAO Development Framework has therefore been assessed through these metrics by its users in the project (i.e. the Application Case partners) and by an industrial entity (i.e. Bombardier). Interesting results have been found. In general, the developed methodology and digital technologies improve the development process in terms of time (several development activities are accelerated), easiness (the transition from document to model-based approach improves the development) and completeness (more activities of a typical Systems Engineering approach are included in the development process). However, not all the development activities report an improvement. In fact, some activities are characterized by metrics with lower scores, especially concerning the *time*. This is indeed the "*price-to-pay*" due to the introduction of new methodology and technologies, which are affected by a "learning curve". However, this can be considered as a positive result of the research, since it provides a roadmap of future development, that can be tackled outside the AGILE 4.0 project.

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9. Copyright Statement

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