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Digital transformation in the European Space Industry

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Abstract

Digitalisation is a trend in most industrial domains. The Space domain has embarked on it a couple of years ago. Starting from a Model Based for System Engineering initiative, the discussion between Space Agencies and Industry has intensified with several topical working groups. The scope has been enlarged, from MBSE, to full engineering digitalisation, aiming at producing the enablers that will allow to develop digital twins. The paper describes and positions the ESA digitalisation project, as a joint Space Community endeavour, proposing a development approach, and giving programmatic elements as well as the initial panorama of MBSE deployment in Space projects.

1. CONTEXT

The **ESA Agenda 2025** [1] is a document prepared by the European Space Agency Director General when he took up duty, and indicating to the Space Community, and in particular the ESA Member's States Delegations, the directions for the next four years. It says in particular:

- *"In Europe, ESA has the unique ability to implement, together with industry, complex and ambitious space missions and programmes on an equal footing with other leading space agencies worldwide. We will ensure that this ESA strength and value is further reinforced."*
- *"ESA will therefore digitalise its full project management, enabling the development of digital twins, both for engineering by using Model Based System Engineering, and for procurement and finance, achieving full digital continuity with industry."*

Digitalisation is the process of representing all the artefacts of space systems under a (structured) digital representation, on which computers can reason and elaborate. The most explicit example of such digitalisation process is the Model Based technique, where the information, traditionally contained in the form of documents, is instead expressed in a set of data, structured into a model. Computers can be programmed to navigate and search into the models, and create relations between associated data, allowing to discover more properties, and to derive added value such as traceability, optimisation, technical budgets, trends, and knowledge.

Digitalisation includes also e.g. databases or excel sheets, or any format where data is structured, curated and associated to a semantic that allows to unambiguously understand it with a computer. This transformation relies on common standards and new infrastructures that facilitate the exchange of data but also the collaboration along the whole supply chain.

2. THE DIGITAL SPACECRAFT

2.1. General Concept

Digitalisation is under way in many domains: automotive [2], railways [3], aircraft [4], construction [5], airports (Schiphol twin) [6], medical [7], Eurocontrol [8].

The Digital Spacecraft is a concept derived from these similar initiatives, and introduced in ESA to cover the digital transformation of space, ground, launcher segments development and operation, as a new way to collaborate within the space ecosystem throughout the full project lifecycle. It is based on digitalisation and combines as an umbrella a wide spectrum of topics like MBSE, digital transformation, digital twins and full data integration into a single consistent concept covering all aspects related to a spacecraft.

Digitalisation is already ubiquitous in the engineering domain. It allows expressing the concept of operations, structuring the requirements, and tracking them through design and manufacturing up to testing. It is intended to support the optimisation of the design, to make informed trade-offs and to clarify the interfaces. It allows the systems engineers and the project teams to master the complexity of the space system, relying on an authoritative

source of truth of the system, communicating knowledge and exchanging data in an unambiguous way. It enables quick access to key parameters via dashboards, understanding the impact of changes and managing those, building knowledge from lessons learned for optimisation and/or for future reuse. It also allows maintaining a continuous and homogeneous flow of information between the different disciplines of the system, along its life cycle, and across its supply chain.

Besides engineering, project management and product assurance are also transitioning to digital, supporting the workflows related to schedule, changes, deviations and non-compliances in an automated, traceable and searchable way. Finally, procurement complements the picture with the digitalisation of the steps included in the preparation of the Invitation To Tender (ITT) package, management of the resulting contract, deliverables, contract change process and the contract closure, associated to adequate legally compliant processes.

2.2. Space domain characteristics

Producing spacecraft would not appear a priori much different from producing aircraft or cars. The overall life cycles are similar (specification, design, manufacturing, tests). However:

- the number of items produced is different: most satellites are one-off (science) or a few are produced (earth observation). The Galileo constellation is the largest, with 24 satellites and 6 spares. Europe is not yet involved in large constellations like Starlink.
- The way to test them is different, as you cannot test-drive or flight-test a spacecraft or a launcher. The overall development process is ruled by specific Standards called European Cooperation for Space Standardisation (ECSS) [9].
- Although Newspace may trigger some changes, supported by ESA Director General, the current spacecraft procurement is specific, generally done by the various European Space Agencies, through a Supply Chain, using ESA Member States budgets distributed according to specific rules.
- These budgets would not allow partnerships like the one signed between Airbus aircraft and Dassault Systèmes to co-engineer the future aircraft and its digital development environment. They would not either allow ESA to impose specific digital technology to the Space industry without consideration of their valuable heritage in the domain.

Therefore, the Space domain must deploy digitalisation in a context constrained by contractual rules, processes, organisation and technological heritage. This boils down to an essential need: interoperability of all the tools, across disciplines, along the life cycle, and through the Supply Chain. This need appeared in 2018 during a workshop organized by the French Space Agency (CNES) on MBSE [10], where it appeared clearly that industry had internally matured some digital technology, but was facing issues in the collaboration between the stakeholders of a project. ESA had therefore a harmonisation role to play.

2.3. A Joint European Vision

Digital transformation of space systems is an ESA Member States endeavour.

Digitalisation is a change process. The key of its efficiency is the digital continuity in the three dimensions of space systems development: disciplines, life cycle and supply chain. This means that all space actors are essential for digitalisation.

Space actors are not progressing at the same pace, though: some are more advanced in functional system engineering, other in manufacturing, disciplines are not evenly digitalised, and principally, The success of the change process will be as strong as its weakest link. Consequently, a widespread, staged development and incremental implementation approach is of strategic importance to bring all industrial actors at the same level, and this is where ESA and its Member States have a role to play.

The most important change lies on the new “ways of working” even more than on evolving the processes and tools. Digitalization is not about doing what we are currently doing better or in a smarter way, it is about changing what we do and the way we do it. The Digital Spacecraft is a way to change drastically the way Agencies, primes and supply-chain work together, switching from a 100% customer/supplier relation to a mix between co-engineering approach and contractual relation. This mind-set change is the key enabler for future European success and digitalization is its enabler. Digital engineering come along with higher transparency, trust, partnership and objectives alignment.

2.4. A multi-level harmonisation forum

Digitalisation involves the space European community through a number of European joint agency-industry working groups led by ESA:

- the MB4SE Advisory Group [11]**
 This group has been established in 2019 with the objective to deploy Model Based System Engineering in Space projects. It includes five space agencies (ESA, CNES, DLR, ASI, and UKSA) and four Large Systems Integrators (ADS, TAS, OHB, and ArianeGroup). It advises ESA on the technical aspects of MBSE research and development, and mainly on interoperability of tools, through the seamless exchange of the associated data.

The MB4SE AG serves as Steering Group of the OSMoSE Governance [12] group. The “Overall Semantic Modelling for System Engineering” initiative arises from the need of enhancing the way information and knowledge is exchanged among the stakeholders involved, enabling efficient interoperability among model-based infrastructures used. The OSMoSE initiative addresses interoperability at semantic level, merging all stakeholder’s concepts into a global conceptual data model resulting in the so-called Space System Ontology (see 3.1).

- the Digital Spacecraft Think Tank [13]**
 This multidisciplinary group has been established in December 2020, with ESA and Industry (i.e. Airbus Defence and Space, Thales Alenia Space, Ariane Group, RUAG and OHB/MT Aerospace). It was established by ESA’s Executive Board to engage in identifying and harmonizing the steps to be undertaken for the digital transformation of the end-to-end space mission development and operation, with the aim to be beneficial for all stakeholders in terms of technical efficiency, schedule and consequently costs. This team was mandated to prepare a detailed plan for the progressive deployment of the Digital Spacecraft approach across the Agency in close cooperation with industry.

The Think Tank is steered by a Digital Spacecraft Steering Committee gathering higher managerial levels of stakeholders in view of endorsing the plans and empowering the teams.

Figure 1 depicts the digitalisation as a rocket, where the stages and boosters are the working groups of industry and agencies, delivering the Digital Spacecraft in orbit... IT platform and Data Management are addressed in 3.3 and 3.4.

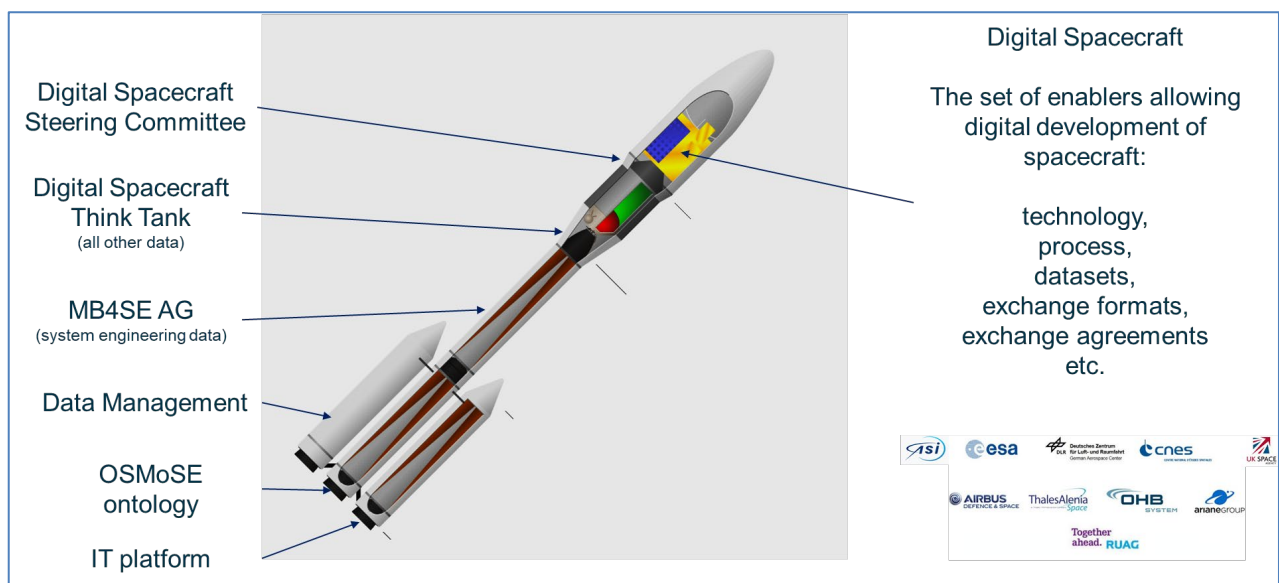


Figure 1 A systematic, multilayer, collaboration

In the Digital Spacecraft Think Tank, several discussions were held on the definition of the Digital Spacecraft and on the support of the “Digital Transformation”, which is a myriad of new thinking and development in the areas of data and lifecycle management, throughout the entire ecosystem, and that can present many unforeseen challenges.

The term “Digital Spacecraft” represents a concept for an end-to-end digital continuous way of working on space missions in the European ecosystem. The Digital Spacecraft is more a set of digitalisation enablers, than a single product, or a particular technology. It includes a number of technologies such as Model Based System Engineering (MBSE), Computer Aided Design (CAD), simulation techniques, Augmented, Virtual and Mixed Reality (AR/VR/MR), Artificial Intelligence (AI) and various communication, collaboration and project control and management technologies at infrastructure level.

Leveraging the new breakthroughs on coupling the simulation results with physical data in continuous synch (digital twin technologies), the Digital Spacecraft allows for feedback and learning (e.g. from operations back to development, and among projects). The Digital Spacecraft therefore enables understanding, learning, reasoning and dynamically recalibrating models, for an improved decision-making.

3. DIGITALISATION IMPLEMENTATION

3.1. Principle

The goal is to identify the digital threads occurring in Space projects, such as to ensure the digital continuity in three dimensions.

- The data shared between disciplines should be defined and understood the same way by everyone, and exchanged continuously between engineers.
- The Spacecraft data state reached at a particular milestone of the life cycle should be propagated in the next phase, in order to ensure traceability and avoid distortion along the development.
- The relationship Customer-Supplier should be based on exchanges of models and data rather than of documents.

To identify the data threads, it is necessary to identify the processes followed by these data, as well as the overall data model. The processes indicate the exchanges between the disciplines or the stakeholder, i.e. the point where we want to be interoperable. Defining process and data at the global level of a spacecraft will fail. Instead, applying the concept of divide and conquer, the identification of processes and data models is first done at discipline level, for which relevant experts can support the local digitalisation of the discipline that they know.

In a second step, putting together the data models shows that some data are shared between disciplines. For example, the system product tree is used by Product Assurance, the centre of gravity of the CAD tool is used by the control system, etc. It is essential that the two disciplines have the same understanding of the shared data: same meaning (dry mass, wet mass), same referential, same units, same structure, same financial reference (for cost data), etc. This means that each data must have a unique semantic for everyone.

Defining the common semantic of data is done at the level of an *ontology*, which is commonly discussed and agreed in the OSMoSE group [12]. Indeed, a set of data can have a physical representation (e.g. XML), a logical representation (e.g. a meta-model), and a conceptual representation (an entity-relation concept, called here ontology). The ontology language selected is ORM [12],[14]. ORM allows to define the agreed entity-relationship of the data set, as well as (thanks to the specific mechanism of “derivation”), any semantically equivalent expression preferred by one or another stakeholder. This semantic equivalence allows generating automatically a physical representation of the data set appropriate for each stakeholder, as well as the tool that translates one format into another one. This allows achieving what is called “*semantic interoperability*” (Figure 2).

It is therefore key that the data sets identified by each disciplines are abstracted into an ontology, all ontologies are harmonised into a single “Space System Ontology (SSO), allowing for semantic interoperability of the tools between the disciplines. This applies in the same way to the exchanges between customer and supplier.

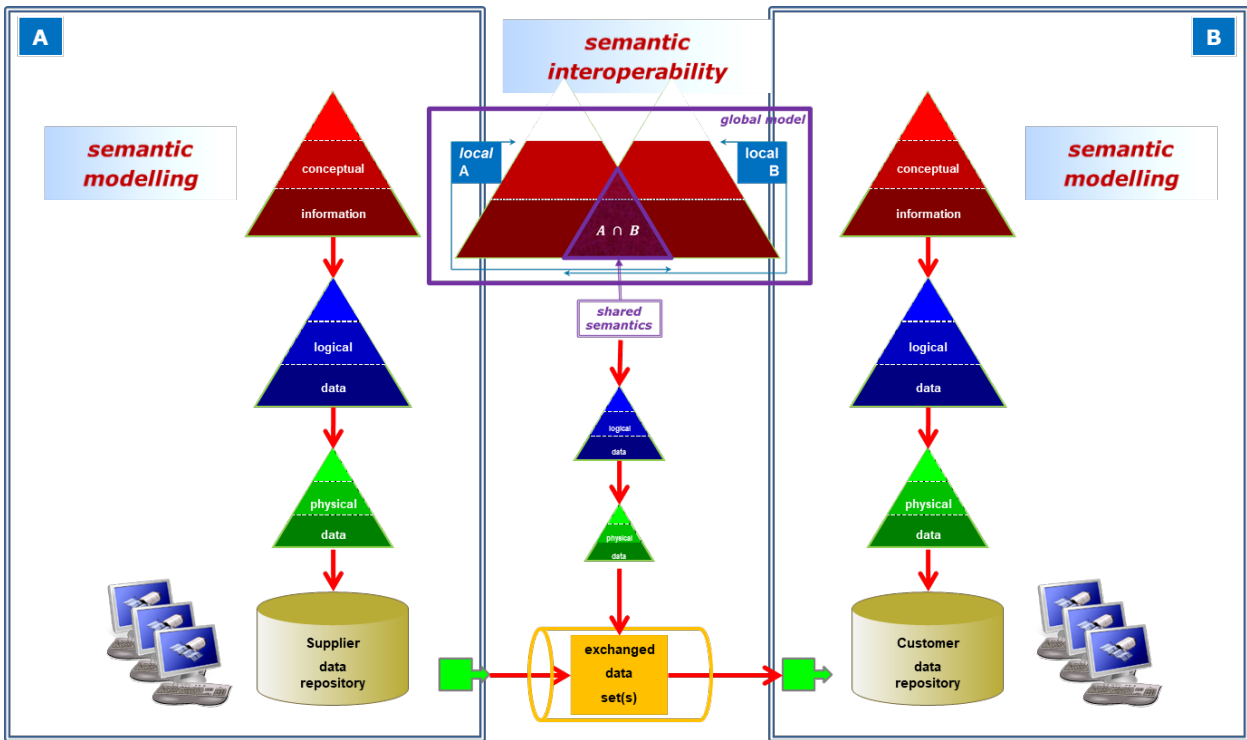


Figure 2 Semantic interoperability

3.2. Application

Figure 3 and Figure 4 illustrate the first steps enabling digital continuity through the development of digitalisation enablers, and in particular

- formalisation of the processes, artefacts and data models of each engineering discipline,
- alignment of the data models with help of the Space System Ontology
- deployment in the Supply Chain to exchanges between each level of the Customer Supplier relationship.

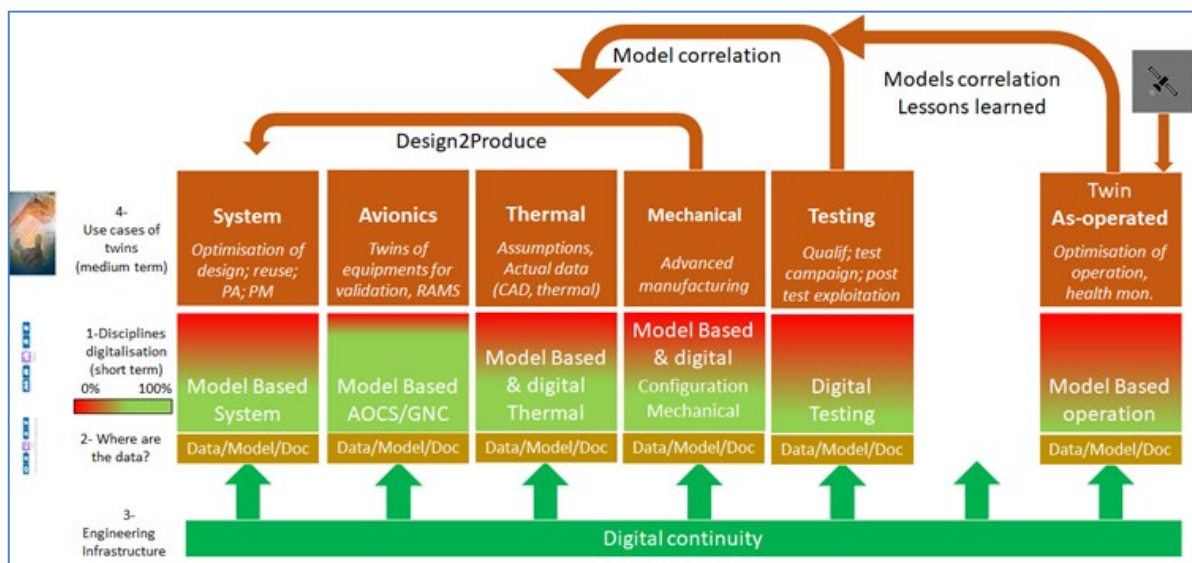


Figure 3 Illustrative example of Digitalisation of each discipline, then digital continuity, then data exploitation

Some disciplines are illustrated here; they need (1) to increase their level of digitalisation, using model-based or other techniques, (2) to identify where are the data in the process, (3) to identify their own set of tools that will later be connected to achieve digital continuity. When these digitalisation enablers are available, data are exploited (4) to optimise and reuse designs, to produce digital twins, to verify test coverage, to make model correlations with the actual data of the physical items. The “as operated” twin is the ultimate achievement allowing managing efficiently the operations of the real spacecraft. Design2Produce is an ESA R&D programme.

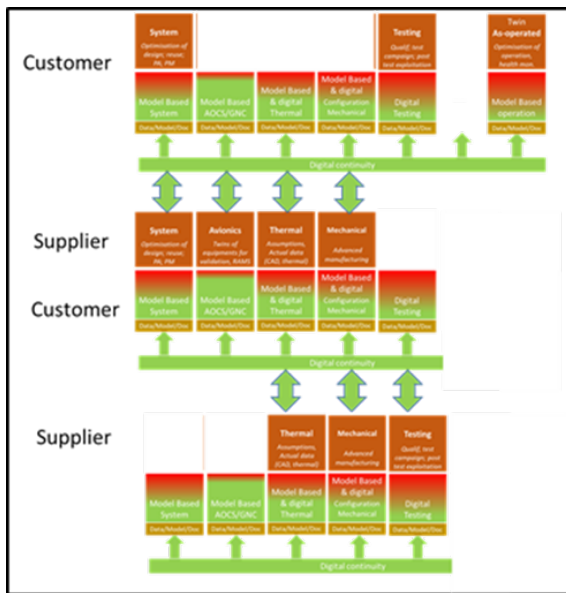


Figure 4 Artist impression of the propagation of digital continuity along the supply chain

The digitalisation enablers are connected through the Supply Chain, generally between the same discipline, allowing experts to work together. Depending on the metier of the Supplier, only some disciplines need to be connected.

3.3. The IT Platform

The next issue is the one of the informatics environment supporting the digitalisation. At ESA, it is called “IT Platform”. It should ultimately be similar to an (Extended) Enterprise Architecture. This paper will not address the “corporate” part of it dedicated to management, contractual or financial aspects.

Figure 5 is an attempt to understand which tools, presently used in ESA, should be connected to ensure digital continuity. The main interest of the figure is its complexity that illustrates the difficulty to implement such a platform. In this figure, all discipline tools are connected to a central exchange tool called “data hub”, making sure that everyone has the right value of the right data at the right time.

Figure 5 is an attempt to understand which tools, presently used in ESA, should be connected to ensure digital continuity. The main interest of the figure is its complexity that illustrates the difficulty to implement such a platform.

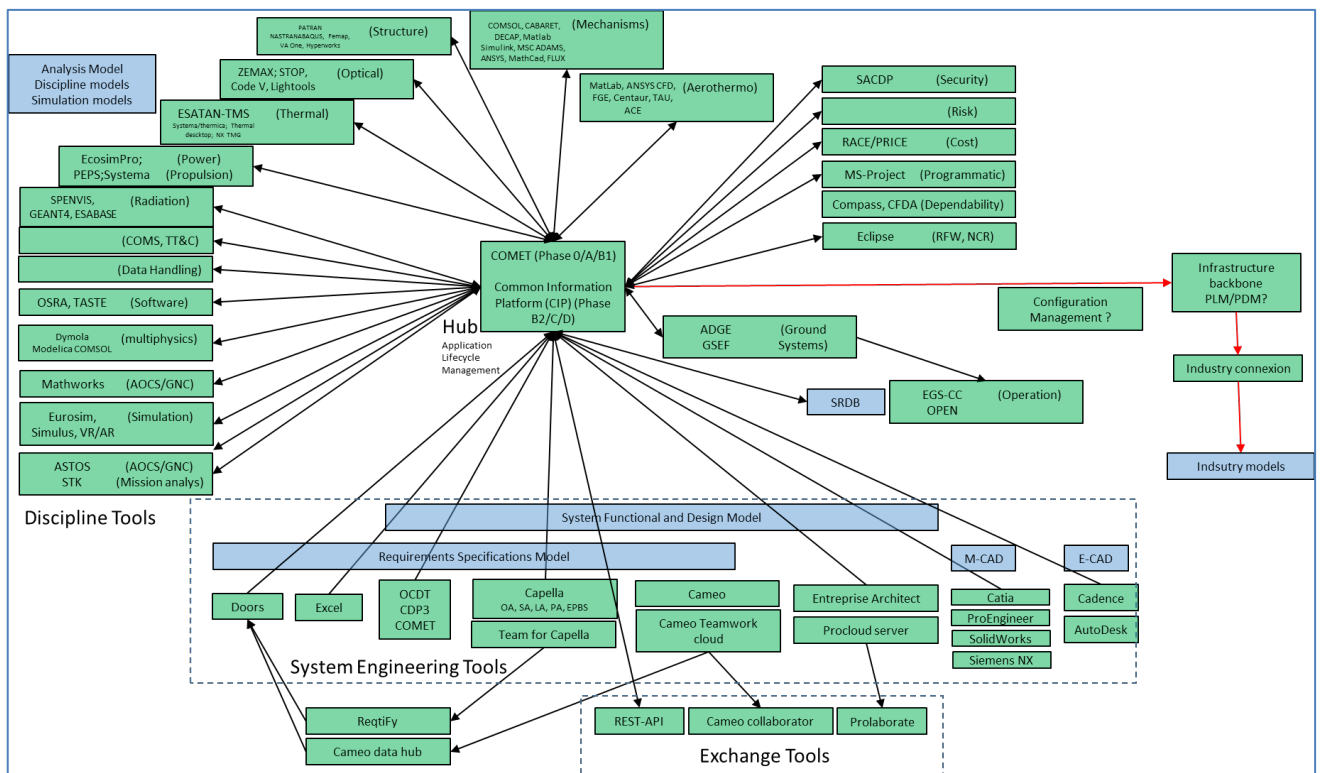


Figure 5 status of spacecraft engineering tools to be included in an IT platform

At the bottom are the system tools: requirement engineering, functional, mechanical, and electrical. The discipline tools come as an umbrella around the central Data Hubs (early phase, later phase, and ground segment specific). The data hub is connected to the IT Platform and the (extended) Enterprise.

This architecture is inspired by the ESA IT platform of the Concurrent Design Facility [15] called COMET [16]

COMET is used in early phases of spacecraft development (called phase 0/A/B1) to centralise all the data of the discipline involved in the concurrent design. Data refreshed by one discipline are immediately pushed to the others. This allows converging quickly during the early mission and spacecraft concept definition. COMET is also used in an activity called Digital Engineering Hub Pathfinder (DEHP) [17], where it intends ultimately to connect all the tools depicted in Figure 6.

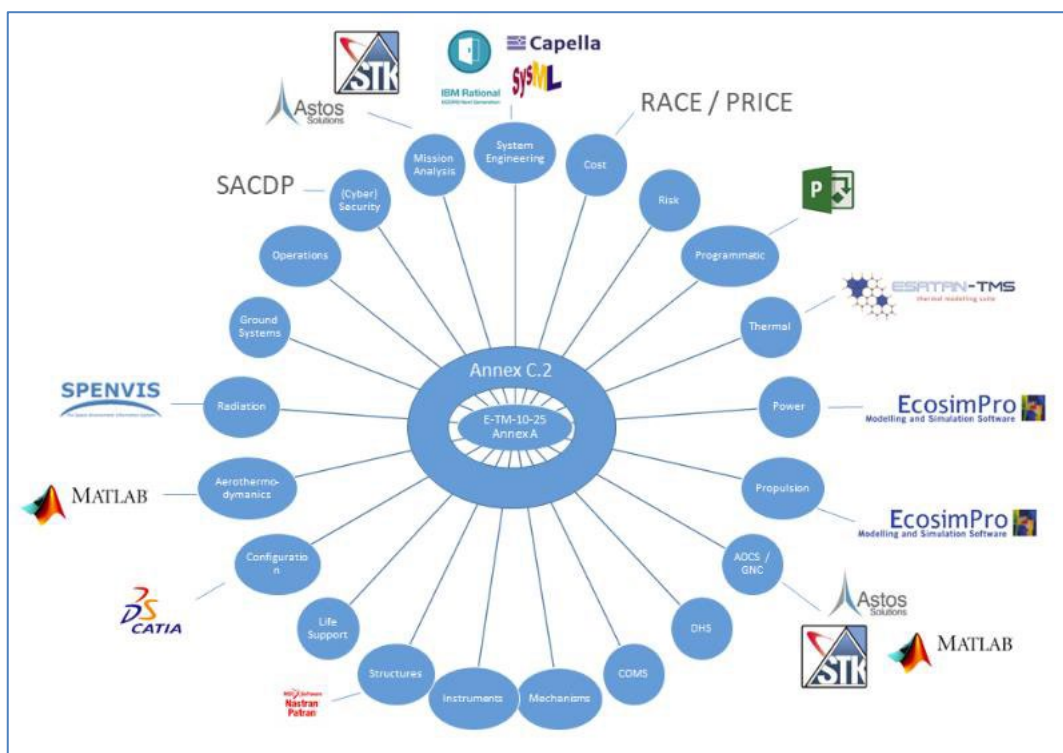


Figure 6 The spoke wheel concept of the Engineering Hub (courtesy Rhea)

This wheel shows that, up to phase B1, the number of tools is “relatively” limited. The complexity arrives in later phases, where the complete workshop of engineering, operations, product assurance and management tools are deployed. ESA is running some activities (not yet completed) to develop Data Hubs for future phases.

3.4. Data management

Digitalisation is not yet fully achieved once data threads are identified and IT Platform is available... Other issues appear such as:

- data ownership and visibility: in the relationship between customer and supplier, the exchange of documents has traditionally allowed the supplier to control the visibility that he wanted to give to his customer on the design. However, “*you cannot hide behind the data*”. Delivering the supplier model can expose a lot of information, including some know-how, to the customer. ESA observes more and more industry reluctance to deliver some models, whereas ESA needs it to perform his tasks. It is important to establish a relation of trust, of course supported in a legal frame, allowing the supplier to know which data are needed by the customer and to do what.
- this applies not only to the verification performed by ESA projects teams on industry design and tests, but also to the ESA reviews. Reviews are milestones in the life cycle where the status of the project is

analysed, is compared to an expected maturity at that stage, and results into mitigation actions to palliate the potential weaknesses. ESA reviews are often done by independent reviewers, working for ESA, but not directly in the project team. This raises the question of visibility that the reviewers should get on the models. It should be enough for them to detect flaws, but less than the one given to the project team. Another issue is the ability of the reviewers to understand models, and the appropriate packaging of these data for reviewers. For example, reviewers could have only a web interface access to the model, supported by documents giving the context of the model, the “user story”.

- security: even with the best trust relationship, informatics exchanges are subject to security threats, and it is vital for companies to implement security measures at all levels. This requires a threat analysis, in order to decide where the protections must be placed. The design of the IT platform is generally necessary to understand where the threats are.

These topics need to be addressed at a different level than the pure technical level. They are discussed in the space community in the Data Management working group, a sub-group of the Digital Spacecraft Think Tank (Figure 1).

4. STATUS IN ESA PROJECTS

To date, digitalisation is mainly deployed in ESA projects through the Model Based System Engineering (MBSE) techniques. It addresses the functional part of the system with some links to physical architecture. But the link with the physical world (CAD, testing, etc.) is not yet achieved. Figure 7 shows the ESA projects implemented with MBSE.

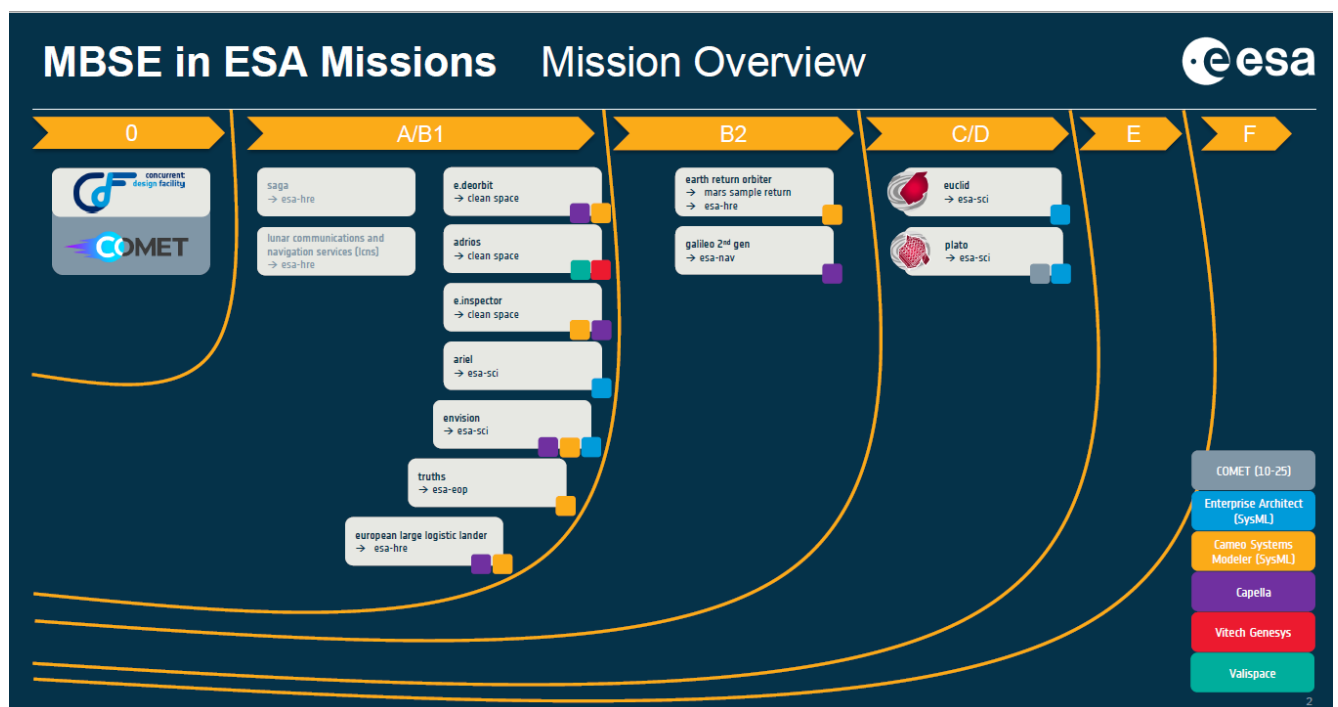


Figure 7 Status of MBSE introduction in ESA projects

MBSE was first introduced in Euclid, thanks to the presence in the team of a SysML guru who needed to solve a particular problem: the payload operation planning. He shared a preliminary model with the scientist community, and they found beneficial to collaborate on it. The model was further developed to include the payload architecture, then the platform/payload interface, etc.

MBSE is now introduced in the beginning of the life cycle, as early as the CDF study in phase 0. Supported by ESA, models are then developed, by ESA or industry, in phase A and B1 and then propagated to phase B2.

ESA is working with Large System Integrators, which uses different MBSE technologies. Tools like Capella, Cameo, Enterprise Architect or Genesys are used for similar purpose of functional description. As said before, it is impossible to impose the same tool to all. For its own purpose, ESA will favour SysML (with a particular profile called “MBSE Space”) and Cameo, although Science projects like Euclid and Plato are based on Enterprise Architect. However, ESA is able to work with any of these tools. A competence centre has been established to provide licences, tool support and training to projects.

In order to prepare the digitalisation of projects, a large R&D plan over 5 years has been established, in a Harmonisation process within Member States, addressing methodology, ontology, tooling, and project deployment. A low Technology Readiness Level call for ideas [18] has been made, resulting in the funding of 22 activities. The difficulty resides in the mandatory coordination of all the R&D activities of ESA and industry towards the same goal of interoperability and digitalisation.

5. TOWARDS DIGITAL TWINS

The availability of digitalisation enablers open the way to the exploitation of data. System engineers have access to dashboards of key parameters offering a synthetic view of the system, allowing design optimisation, traceability to reply to such questions as “What if this equipment is not compliant?” or “what if I introduce this change?”.

Further, the measure of the real values of the data on the physical items can be fed back into the models used for the design (this is called “model correlation”), allowing to sue better models in the next project (thermal models, structural models, environmental models, control models, etc.).

The same applies to simulators, which –when fed with the real data of the physical item measured during operation – becomes dynamically representative of the physical item, and are called digital twins. Twins of avionics equipment may be used to anticipate software verification before the availability of the hardware. With proper mechanical sensors inserted in the structure (e.g. with use of Advanced Manufacturing methods), a twin of the structural model can be produced. Finally, the connexion of the operational simulator to the real telemetry downloaded from the spacecraft allows having a spacecraft twin, representative in real time of the real one, and much closer to the one located at hundreds or millions of kilometres... Failure investigation and operation optimisation and prediction are example of capabilities enabled by the digital twin.

Beside the Spacecraft related twins, ESA (through the Earth Observation directorate), has launched the Digital Twin Earth [19]. It will help visualise, monitor and forecast natural and human activity on the planet. The model will be able to monitor the health of the planet, perform simulations of Earth’s interconnected system with human behaviour, and support the field of sustainable development, therefore, reinforcing Europe’s efforts for a better environment in order to respond to the urgent challenges and targets addressed by the Green Deal.

Similar twins for e.g. scientific data of the universe, or human data of astronauts, are investigated.

6. CONCLUSIONS AND RECOMMENDATIONS

Empowered by the Director General, in line with the strategic technology objectives, ESA has embarked in the change process to digitalisation. ESA is not alone. The change is supported by, and performed together with, the whole space community, national Space Agencies, and Industry.

Aiming at the digital continuity in space projects thanks to the interoperability of tools, a step-wise approach is planned. Many local progresses have been made, but the dots need to be connected. Several discussion forum are organized, allowing Agencies and Large System Integrators to progress together within industrial or programmatic constraints. The next step is to involve better the low end of the Supply Chain.

The main challenges are to maintain the synchronisation of the whole process, to keep awareness by dissemination, to convince gradually all the community without imposing, to ensure the communication of the progress and difficulty between all the actors such that we can solve the problems together, and to survey any opportunity to introduce digitalisation.

Beside the technological challenges, data management and governance is an essential topic to be addressed together, without which the whole initiative could fail.

But the success already observed, and the positive feedback received by project managers and industry, indicates that we are in the right direction. Let us get digital!

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Space organisations landscape		
<u>Space Agencies</u>		
ESA	European Space Agency	https://www.esa.int
CNES	Centre National d'Etudes Spatiales	https://cnes.fr
DLR	Deutsches Zentrum für Luft- und Raumfahrt	https://www.dlr.de
ASI	Agenzia Spaziale Italiana	https://www.asi.it
UKSA	United Kingdom Space Agency	https://www.gov.uk/government/organisations/uk-space-agency
<u>Space Industry</u>		
ADS	Airbus Defence and Space	https://www.airbus.com/en/products-services/space
OHB	Otto Hydraulik Bremen	https://www.ohb.de
RUAG	Rüstungs Unternehmen Aktiengesellschaft	https://www.ruag.com
TAS	Thalès Alenia Space	https://www.thalesgroup.com/fr/espace