POLARIS

TECHNICAL REVIEW
INNOVATION JOURNAL

DIGITAL INNOVATION

Enabling the bonding of a multi-domain

52-2025

LEONARDO

contents

editorial

Dear colleagues, readers, technology fans,

it is a pleasure and a privilege for me to introduce to this issue of our long-standing technical review POLARIS Innovation Journal.
I have been an eager reader for many years and today honoured to chair such collection of digital enabler examples of technology at the heart of the digital transformation of our business proposition.
The transition journey from Leonardo's technological heritage to its digital future is embedded in the vision of the "Digital Continuum". The mission to go "Beyond IT" stands in the challenge to turn Leonardo into a global digital player in the Aerospace, Defense & Security arena.
The industrial plan launched in 2024 by the CEO and GM Roberto Cingolani, calls Leonardo to become a Digital Enterprise, which means acquiring the culture of fostering business with a purposeful "Digital First" mindset, and to master innovation driven by digital trends.

Digital First means approaching any new opportunity or problem with the ground assumption that solutions and innovation should be as digital as possible. This applies to all areas of the company from the supply chain (nationally) to business modelling (globally).
Digital Enablers Strategy of Leonardo seeks to bring this Digital First vision to life, ensuring Leonardo continues to be competitive and innovative in the digital age for its customers and employees.
In a world where:

- By 2026, machine customers will generate $10 trillion in annual revenues.
- By 2027, there will be more smart robots than frontline workers in manufacturing, retail, and logistics due to labour shortages.
- By 2028, largest constellations of thousands mini-micro satellites will provide global connectivity and unpredictable new services.

Leonardo foresees the need for growing the digital dexterity of its employees, considering new emerging technologies such as AI continuing to mine ground rules of the labour world - whether we like it or not.
What is key now is to learn how to deal with these unavoidable changes.

In Leonardo, we must reshape our enterprise research and development model based on digital enablers. To support this increasing level of digitalization we must invest in training and enablement of talents in technologies like: AI, cloud, digital-twin, high performance computing and data-centric services.

To solve the complexity of tomorrow, Leonardo's primary focus must be to bring together a range of competencies, primarily digital skills with domain-specific knowledge (within a multi-domain business).

The traditional separation between IT / Digital and Business Products and Services is legacy. It is imperative that digital technologies become the proactive enablers of integrated forces that put together both physical and digital worlds to jointly develop innovation being demanded.
It is worth to be aware of how just a dozen of technical papers in this magazine can't fully represent all the magnitude of the industry leading technology exploitation across Air, Land, Sea, Cyber and the Space sectors Leonardo serves, as well as the geographies, including Italy, UK, USA, Poland, Switzerland and much more wherever else our ingenuity is creating new secure solutions for products, processes and services.

However, we have selected some representative examples summarized here. The first article provides a clear and growing consciousness towards "Blue" (digital) and "Green" (sustainable) are ascendible twins of transformation to Leonardo.

Leonardo's Digital-First Journey is shaping the Future of National Security in domestic countries, as in the UK (article 2) where a Data-Highway is connecting cross-geographies of the company and harnesses collective ingenuity to deliver groundbreaking solutions. It is the Digital Continuum that bridges the gap between research and production, leveraging advanced AI, synthetics environments and cloud-based platforms to test and refine technologies efficiently, which allows Leonardo to "fail fast" without incurring significant costs.

Article 3 introduces the Davinci-1, the HPC infrastructure that is shaping the new digital future in Leonardo addressing challenges like the numerical multidisciplinary simulation of Hypersonic Flows (article 4) or the Digital Engineering techniques applied to improve accuracy of multi-physics models (article 5) that are evolving even the more recent model-based system engineering approaches for rotorcraft development.

Wherever, Artificial Intelligence applications are impacting Leonardo's branches spanning solid value over old and crestfallen expectations like the need for real-time, reliable data across all stages of the product lifecycle, which has become paramount for driving innovation thanks to the One-PLM concept (article 6). The single-source-of-truth platform for engineering-manufacturing-in service data at Leonardo's Divisions is providing many products and certification processes with the unique solution and set of skills waited for decades.

Additionally, Leonardo's commitment to AI assurance makes these systems reliable, ethical, and effective. It addresses specific threats to AI technology, while safeguarding its application in high-stakes environments.

Digital Twin for Production Processes together with Training of Plant Operators are the key elements of giant transformation achievement like the NEMESI programme (article 7) for the life cycle of airworthy primary structures, as well as the newest Closed Loop Manufacturing is the digital approach to mechanics' discrete and electronics production (article 8).

In closing this issue, article 9 illustrates an ecosystem of solutions based on the digitisation of processes and simulation methods using state-of-the-art Model Based System Engineer techniques.
In the end folks, this calls to further challenges like the international programme for the 6th generation fighter. Most of advanced developments, such as the GCAP programme for future air superiority, are likely to include a swarm of loyal wingmen differing in type and lethality around a core platform, all connected within a wider net-centric defense ecosystem. This is the perfect example of the vision needed to achieve the bold Defense Industry ambition to deliver the benefits of world class military/dual use capability. These topics will be explored in a next issue of Polaris Innovation Journal.

Freedom of action and freedom of modification, participation to business joint ventures, prosperity of corresponding Nations, affordability, industrial return, and sustainability are key milestones of any modern Defense and cutting-edge programme. Operating in an increasingly complex, contested, and undefined battlespace, such environment shall be enabled by a cornerstone of collaboration: the digital backbone.

Our dream is to see in few years Leonardo become a "Digital First" company, which means that all of us **look at every Digital Innovation as an opportunity to be part of such backbone for peace, security, and prosperity.**

Many thanks to all of you, fellow digital transformers.

Head of Digital Solutions and Engineering
PhD, Francesco Rogo

Blue and Green Digital and Sustainable Transformation

Caterina Rapisarda, Christian Giusti, Mario Lombardo, Marta Cordoni, Michele D'Urso, Paolo Grumelli, Roberto Lalli, Salvatore Musto, Stefano Pagliai

Leonardo - Electronics Division

This paper explores the Blue and Green Twin Transition within Leonardo Electronics Division: "Blue" represents Digital Transformation and "Green" aims toward Sustainability. The paper examines the interplay between these two transformations and, more specifically, focuses on how Digital Transformation can support and enable Sustainability.

INTRODUCTION

The era we are currently experiencing can be best characterized by the term "Transformation", where the focus extends beyond products and the value creation, to encompass the processes driving new models of business. This approach emphasizes flexibility, configurability, and environmental protection. For Companies operating in the Aerospace and Defence sectors, **Digital Transformation (DT)** is undeniably a game changer that not only influences the types of products and processes developed, but also reshapes the way business is steered.

Moreover, in recent years, there has been an increase of demand for business models in which growth and innovation go hand in hand with environmental and social responsibilities.

This is achieved through development of guidelines that adhere to the three pillars of Sustainability (i.e. Environmental, Social and Economic) and the seventeen **Sustainable Development Goals (SDGs)** set by the United Nations. In this scenario, we can consider a double transformation that is Digital and Sustainable: the so-called Blue and Green Twin Transition, where "Blue" represents Digital Transformation and "Green" aims toward Sustainability.

This paper explores the Blue and Green Twin Transition within Leonardo Electronics Division by going through the interplay between these two transformations. More specifically, it deals with how Digital Transformation can support and enable Sustainability.

The paper is organized as follows:

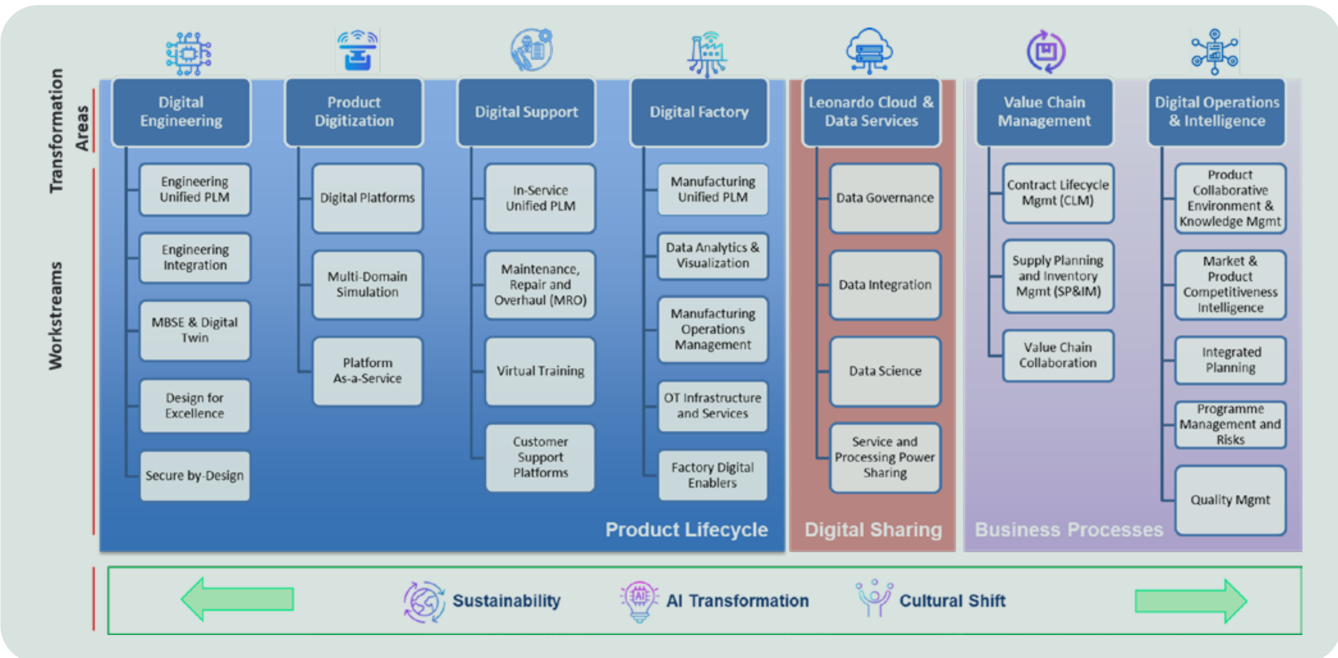
- The core concepts of Digital Transformation and its Taxonomy are presented;
- The Twin Transition — Blue and Green — is analysed, focusing on how Digital Transformation can support Sustainability;
- Next, we provide the perspective of how the Product Digitalization and the Digital Factory can contribute to Sustainability;
- Then, we share golden rules to reach a sustainable DT, that means use and develop of Digital Transformation with sustainability considerations in mind;
- Finally, we turn to **Artificial Intelligence (AI)** — one of the main drivers of the two transformations — through two use cases that demonstrate how AI can support Sustainability.

WHY DIGITAL TRANSFORMATION MATTERS

Today, Digital Transformation has evolved from a buzzword to an existential priority for a large industrial enterprise such as Leonardo. Being it no longer confined to enhancing operational efficiencies or updating legacy **Information Technology (IT)** systems, Digital Transformation now represents a strategic move that reshapes the way businesses operate, compete, and deliver value. It's a journey powered by technologies like Artificial Intelligence, Cloud Computing, Internet of Things, Big Data, and Advanced Analytics, but its essence lies in strategic vision and cultural shift.

To navigate complex markets, interconnected supply chains, and ever-changing customer demands, embracing Digital Transformation is not just an option, but it is a strategic imperative to stay competitive in our era defined by speed and adaptability.
Digital Transformation enables Companies to anticipate market trends, personalize customer interactions, and innovate faster than ever before. These points are all critical for maintaining the competitive edge in a rapidly evolving industrial landscape.
The transformative potential of digital technologies spans across three major dimensions: industrial processes, customer experience, and business models. In Operations, Advanced Analytics and AI optimize production lines, reduce the downtime, and streamline supply chains, bringing about what is the so-called “Industry 4.0” revolution.
Predictive maintenance and real-time monitoring systems enable reducing costs and boosting reliability. In terms of customer experience, Product Digitalization and digital platforms now provide complete flexibility to tailor product features and performance to specific operational scenarios.
A notable example is the **Global Combat Air Programme (GCAP)** system, based on the **Freedom of Action (FOA)** and **Freedom of Modification (FOM)** concepts, enhancing the system capabilities while improving its adaptability and configurability. Finally, on the business model front, Digital Transformation allows enterprises to rethink traditional paradigms. Subscription-based services, Digital Twins, and platform-based ecosystems are replacing traditional business models, thus creating new revenue streams and fostering deeper relationships with stakeholders.

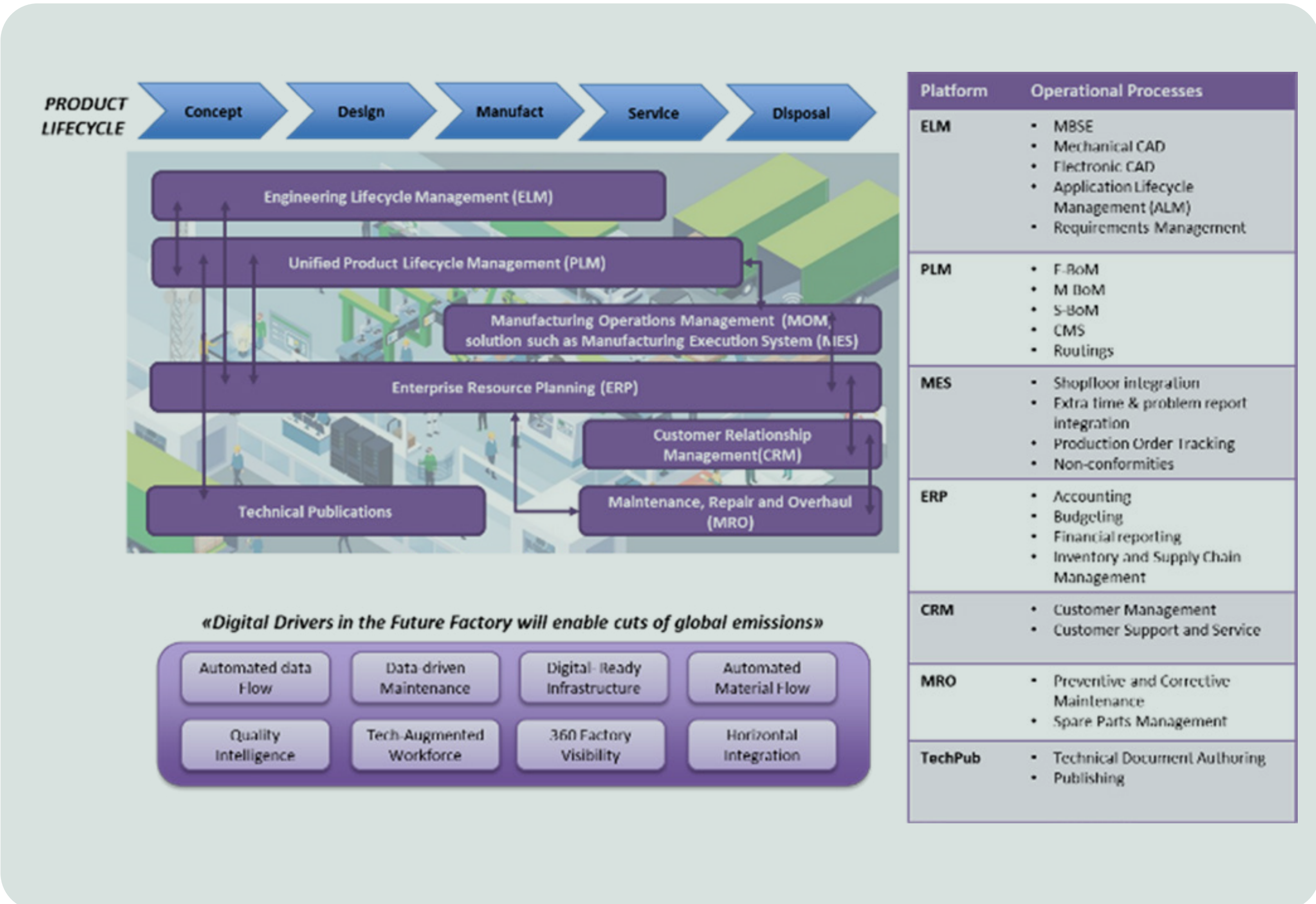
For the Leonardo Electronics Division, the stakes are exceptionally high, as modern defense operations require unprecedented levels of sophistication and responsiveness. This capability is driven by Digital Transformation that serves as a catalyst for innovation and operational success. By harnessing digital technologies, such as edge computing for real-time data processing, Artificial Intelligence, and Secure Cloud infrastructures for global data accessibility, we can address the complexities of multi-domain operations, while adapting to evolving threats and technological advancements.
To effectively implement Digital Transformation, we have identified seven key Transformation Areas, each designed with specific goals to address distinct aspects of the organizational shift. These areas act as the pillars of a structured approach to modernization, ensuring seamless and strategic execution of initiatives and form the Digital Transformation Taxonomy (Figure 1).
Digital Engineering is one of the most relevant areas, aimed at revolutionizing the engineering landscape by enhancing design processes, enabling virtual prototyping, and leveraging Digital Twins, to drive continuous improvements. This transformation area focuses on modernizing engineering capabilities, integrating advanced tools, and ensuring the accessibility of engineering data across the enterprise, laying the groundwork for a modernized, agile, and efficient engineering function. The implementation of integrated tools, **Model Based System Engineering (MBSE)** methodologies, and Digital Twins, not only streamlines processes but also fosters innovation, reduces risks, and drives cost savings.



1-The seven Key Transformation Areas

These efforts, combined with a broader Digital Transformation strategy, ensure that the organization remains at the forefront of its industry, delivering superior products and services in a competitive market. In today's rapidly evolving market, the **Product Digitalization** transformation area becomes a critical driver for business growth and innovation. By enhancing physical products, components, or systems with digital capabilities, we can unlock new revenue streams, develop innovative business models, and plan advanced digital roadmaps. Product Digitalization transforms traditional offerings into intelligent and connected systems that deliver greater value to customers, while enabling superior performance, flexibility, and scalability. Hardware reduction and Reliability improvement can greatly contribute to Sustainability along the In-service phase of the Product Lifecycle Management.

The **Digital Factory** transformation area is dedicated to modernizing and digitizing the manufacturing landscape, by leveraging cutting-edge technologies to automate processes, optimize operations, and enhance decision-making. The initiatives in this area focus on seamlessly integrating digital tools into manufacturing workflows, enabling advanced capabilities such as automated quality control, predictive maintenance, and performance tracking. The goal includes not only the digitalization of the main processes, but also their integration to allow any User to reach useful data since any start point and mostly improve efficiency. The integration of **Product Lifecycle Management (PLM), Manufacturing Operations Management (MOM)** and **Enterprise Resource Planning (ERP)** platforms together and with the other relevant digitalized main processes is crucial to achieve synergistic management of all phases of the product life cycle, from the cradle to the grave. Leonardo Electronics Division is working in this direction. Figure 2 shows the objective picture to achieve. The PLM system connects Engineering and Manufacturing and fosters collaboration and streamline operations, reduce manual intervention, enhances accuracy and speed, while advanced analytics and visualization tools ensure that all the stakeholders can access and act on real-time information.



2-Integrated Product Lifecycle Processes Digitalization for the Future Factory

Digital Support leverages cutting-edge technologies such as AI, automation, and advanced analytics to deliver proactive, efficient, and highly personalized customer service experiences. By integrating these tools, we go transforming our customer support operations, ensuring convenience, responsiveness, and long-term sustainability of the products we deliver. The Unified PLM system extends beyond design and manufacturing to in-service product management, ensuring lifecycle data consistency across service and maintenance stages. Digitalizing **Maintenance, Repair and Overhaul (MRO)** process streamlines the maintenance lifecycle for systems and equipment, while **Virtual Reality (VR)** and **Augmented Reality (AR)** transform the training environments. By incorporating digital support tools and emphasizing the sustainability of its in-service products, Leonardo Electronics Division can remain competitive in today's fast-paced, customer-centric markets while improving operational efficiency and fostering stronger, long-lasting relationships with our customers.
Other significant transformation areas of the Digital Transformation Taxonomy are:

- **Leonardo Cloud & Data Services**, enabling effective data governance, data flow integration, data science, and scalable computing power leveraging the Leonardo's secure cloud infrastructure;
- **Value Chain Management (VCM)**, which focuses on optimizing the interconnected processes that drive procurement, supplier relationships, and resource utilization across an enterprise.

Finally, the **Digital Operations & Intelligence** area provides the foundation for improved product development, market responsiveness, strategic alignment, and a sustainable digital roadmap, completing our comprehensive Digital Transformation strategy with critical components, such as the Product Collaborative Environment (PCE). PCE is the tool for Products Catalogue and its related Investments management, Knowledge Management, Market & Product Competitiveness Intelligence, Integrated Planning, Program and Risk Management, and Quality Management.
Digital Transformation is not only about integrating advanced technologies, as it requires also a fundamental cultural shift across the organization.
To succeed in a digitally transformed environment, we must move away from traditional siloed ways of working and go fostering a culture that embraces collaboration, agility, data-driven decision-making, and continuous learning.
Creating a forward-thinking mindset involves encouraging employees at all levels to view Digital Transformation as an opportunity rather than a challenge. Digital Transformation thrives on cross-functional teamwork using integrated digital platforms to achieve shared goals.
By implementing these interconnected initiatives, Leonardo Electronics Division achieves its end-to-end Digital Transformation, fostering innovation, efficiency and resilience across operations, customer support, and the value chain. This holistic approach positions us to thrive in an increasingly complex and competitive landscape.

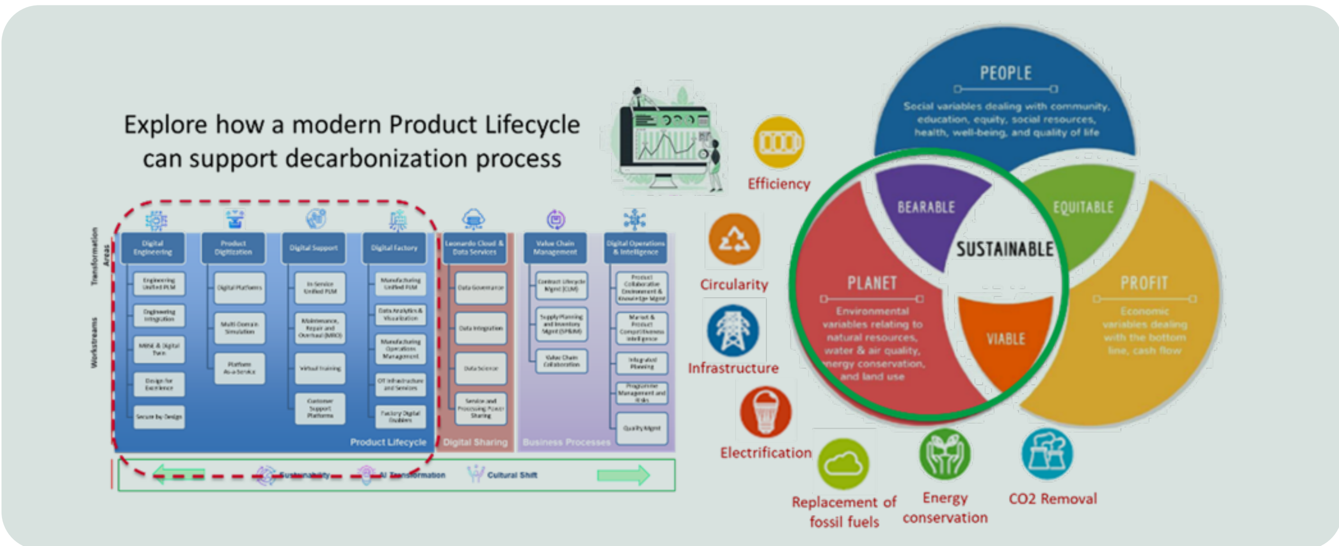
THE TWIN TRANSITION – TOWARDS A BLUE & GREEN FUTURE

The Twin Transition has now become part of the common language, as in our world climate change and worsening environmental conditions represent an existential threat. With Digital Compass and Fit for 55 Policy Package, the European Union (EU) aims at a deep Digital Transformation as well as an internal reduction of net gas emissions at least 55% (compared to 1990 levels) by 2030, with the ambition to reach neutral continent by 2050.
In this global scenario, we try to figure out how Leonardo Electronics Division can contribute to this, and how it is designing its products and processes to ensure that the two transitions can go hand in hand (Figure 3).
Let us start to face the subject from the two different points of view highlighted Figure 4. The first point of view refers to how the use of Digital Technologies can improve the impact on Sustainability, both in the products and in the Company processes.
The second one focuses on developing low-environmental impact Digital Technologies.

3-Digital and Sustainable transformation

Although Sustainability should be addressed in its entirety, with the three main pillars, *Planet, People* and *Profit*, the *Planet* (that means decarbonization process) is the most relevant in this context, which should be accompanied by the right *People* approaches, change attitudes and skills, for a positive impact on *Profit.*
Therefore, the main question is how the Digital Transformation affects the decarbonization process and which of digital subprocesses, following the taxonomy in Figure 5, should be considered the more relevant ones to set the stage.
Figure 5 shows that the Blue zone of the Taxonomy (the product lifecycle Digital Transformation) plays the most important influence on the decarbonization process, the Green zone of the Sustainability. In the specific, the Blue zone affects two, Efficiency and Circularity, of the seven domains of Sustainability [1].
In order to figure out how the Blue zone can affect the Green one in Leonardo Electronics Division, the next paragraph describes two different points of view, respectively the product digitalization and the factory digitalization.

4-The Twin Transition points of view



5-The aim is to evaluate relationship between the Blue zone of the Taxonomy and Green part of the Sustainability

ENABLING DECARBONIZATION

This section presents two different representative views describing how the Blue zone of the Taxonomy enables decarbonization:

- Design, develop and service of a Digital Product;
- Digital Factory.

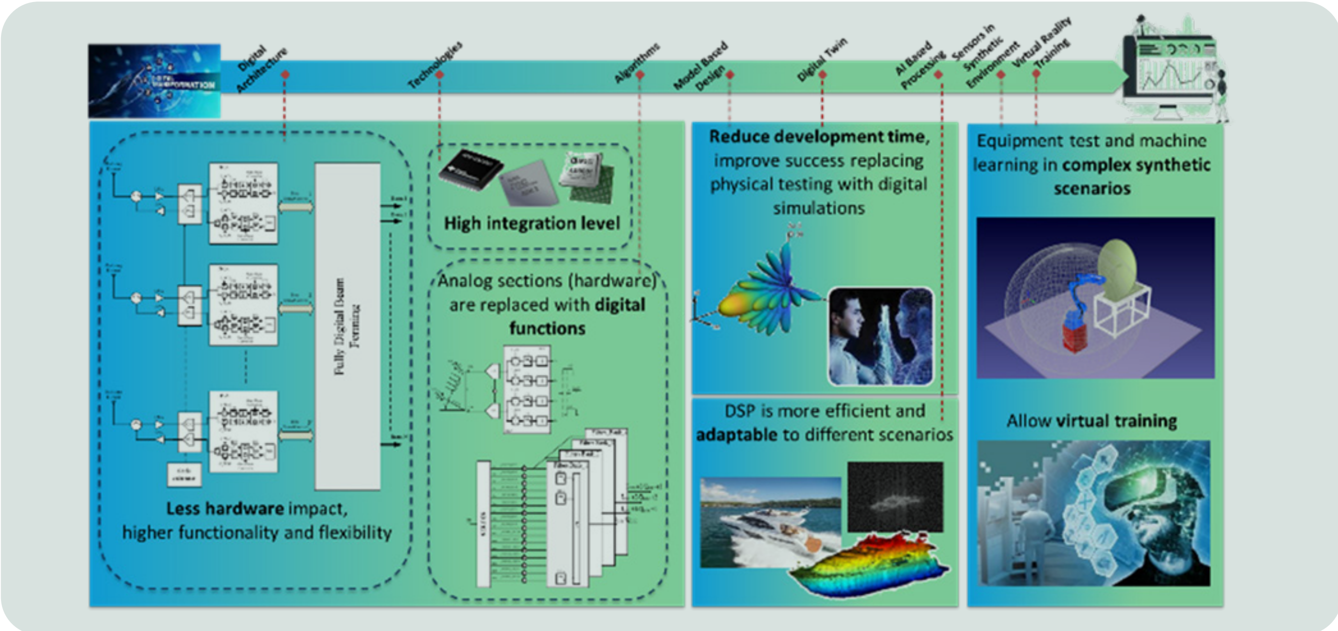
Design, develop and service of a Digital Product shows a high-level view of a representative Digital Product, developed and managed in digital way, in Leonardo Electronics Division (e.g. Radar and/or Communications system).

In this context, the term Digital is applied to different topics such as:

- The typology of the product (i.e. Full Digital);
- The process followed for the product design (MBSE and Digital Twin), AI based signal processing, integration in synthetic environment and virtual training.

Figure 6 describes that view. In this case, Digital Engineering, Product Digitalization and Digital Support are the main areas of the taxonomy contributing to the digital transformation.

As reported in Figure 6, Digital Transformation affects the nature of the product itself, with fully digital architecture, state of the art components that increase the level of integration, unconventional signal processing algorithms, and use of AI based technology. Digital Transformation affects the processes applied to design and development of the product, such as MBSE and Digital Twin, test and integration of the equipment in synthetic environment, and virtual training.
To fully understand how these aspects can improve sustainability, let's consider how the use of a digital architecture leads to reduction of hardware (there are less different part numbers to manage), and how the use of the new digital components, along with unconventional signal processing, operate as enablers to such a kind of architecture.
On the other hand, let's consider how digital processes, such as Digital Twin as well as integration and test of the equipment in synthetic environment can lead to time reduction, physical parts, field tests, environmental pollution, thus contributing to decarbonization.
The second view describing the relationship between Digital Transformation and Sustainability regards the Digital Factory (Figure 7).



6-Design, develop and service of a digital product

7–Digital factory for Sustainability

All the workstreams under the Digital Factory area of the Taxonomy contribute to decarbonization:

- *Manufacturing Unified PLM*
  With a complete visibility across the entire Product Lifecycle (PL), redundancies and inefficiencies are reduced. By tracking product components and materials throughout their lifecycle, unified PLM supports strategies for reuse, remanufacturing and recycling, helping also in meeting regulations and sustainability standards and in creating reports to regulatory bodies and stakeholders.
- *Data Analytics & Visualization*
  Make it possible to identify inefficiencies, optimize production and reduce waste and consumption by analysing real-time data on energy and materials (e.g. predictive maintenance, energy monitoring of production assets).
- *Manufacturing Operations Management*
  Scheduling and execution of production activities can be set to optimize energy efficiency and emission reductions. Digital integration among PLM, ERP and MOM ensures a paperless approach with a positive impact in terms of water, energy and carbon footprint reduction.
- *OT Infrastructure and Services*
  The OT (Operation Technology) infrastructure enables the centralization of different application services on a virtualized infrastructure, resulting in a reduction of energy and space consumption. OT services enable remote activities on shop floor systems, ensuring more efficient transportation and reducing fuel consumption.
- *Factory Digital Enablers*
  Usage of tools and assets that supports manufacturing process automation increasing efficiency and reducing energy consumption (e.g. virtual/augmented reality, remote inspection digitalization, smart asset management).

SUSTAINABLE DIGITAL TRANSFORMATION

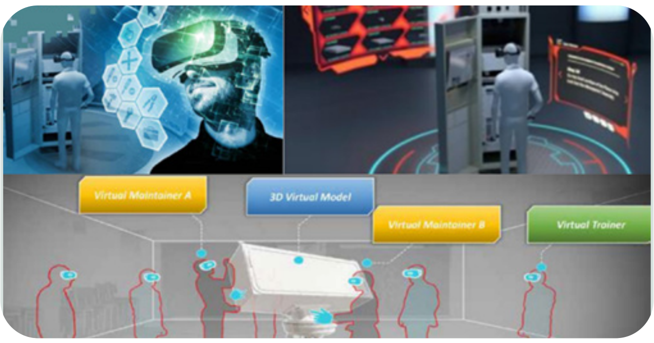
After having analysed how Digital Transformation supports and enables Sustainability, with a focus on the decarbonization process, this section describes golden rules that help reaching a sustainable Digital Transformation, which means to use and develop Digital Transformation by keeping sustainability considerations in mind:

- *Green IT Infrastructure*
  Implement energy-efficient data centres, cloud computing, and edge computing solutions to minimize energy consumption. Adopt renewable energy sources to power digital infrastructure and optimize server utilization to reduce carbon footprints.
- *Remote Work and Digital Collaboration*
  Encourage sustainable work practices by implementing digital collaboration tools that reduce the need for travel and minimize office space requirements. Remote monitoring and predictive maintenance of industrial systems can also reduce on-site interventions, lowering carbon emissions. Golden rules for a sustainable use of Digital.
- *Sustainable Software Development*
  Develop and use software that is optimized for energy efficiency, reducing computational power where possible. By adopting green coding practices, you can minimize the energy consumed by digital solutions.
- *Lifecycle Management of Digital Tools*
  Ensure that digital devices and hardware are designed, used, and disposed of Sustainably. Use eco-friendly materials in hardware production, implement take-back programs for recycling, and extend the lifespan of devices through maintenance and refurbishment.

VIRTUALIZATION AND SUSTAINABILITY: MORPHEUS XR USE CASE

Morpheus XR (MXR) is an innovative technological solution transforming the way maintenance technicians are trained. Through its extended reality (XR) environment, it combines efficiency, safety, and sustainability, enabling training sessions without relying on the physical availability of the product and redefining traditional approaches.

Morpheus XR allows technicians to interact with virtual mock-ups of the components that make up complex products. Through realistic simulations, users can familiarize themselves with the product's structure and perform operational and maintenance procedures in a controlled, virtual environment (Figure 8).



8-Morpheus XR

The key benefits of Morpheus XR are:

- *Accessibility and Flexibility*
  Training can take place anytime and anywhere, regardless of the availability of the physical product. It provides an immersive and interactive experience that enhances hands-on learning.
- *Environmental Sustainability*
  MXR reduces the consumption of raw materials and energy needed to produce physical units for training and contributes to lowering CO_2 emissions and conserving freshwater, supporting corporate sustainability goals.
- *Enhanced Safety*
  MXR reduces the risk of injuries during training by providing a secure virtual environment and minimizes the possibility of damage to real products caused by human errors during practical exercises.
- *Cost Efficiency*
  MXR lowers expenses associated with producing physical units specifically for training purposes and decreases costs related to repairing damages caused during traditional training processes.

Morpheus XR, by eliminating the need for physical products in training, promotes a sustainable training model. The reduction in material and energy consumption results in a lower environmental impact, aligning with the shift toward more responsible business practices. MXR is not just a tool for improving training effectiveness but also a cornerstone for a more sustainable and secure future. Its ability to integrate technological innovation, environmental conservation, and worker/product safety makes it the ideal choice for companies looking to modernize their training processes.

AI AND SUSTAINABILITY: TWO USE CASES

USE CASE 1: Realistic Synthetic Dataset Generation

The first use case is related to Machine Learning and, in particular, to the problem of training Deep Learning Models. This class of models allows solving very complex tasks that most of the times could not be addressed with traditional algorithms (for example, let's think about the function of automatic object detection and recognition). The problem that arises when using Deep Learning Models is that they are data-driven, which means that they need massive datasets to be properly trained. In most cases (especially in military domains), these datasets are either not available or difficult and very expensive to provide (for example, through acquisition campaigns that should involve hundreds of military vehicles for a very long time).

For this reason, in the latest years data scientists have been trying to overcome this problem by generating synthetic datasets, starting from 3D models of the objects of interest, and using image generators to produce synthetic pictures. Figure 9 shows the example of an Eurofighter picture generated by VIR3X, Leonardo's Image Generator.

This solution allows generating millions pictures of many objects operating in different scenarios and environment conditions, which can be used to train very large deep learning models.

Although the performance of a Neural Network trained in this way is very good when tested on synthetic images (which means that the training phase has been successfully completed), when it is deployed in the real world, it does not perform as good as it was expected to do. This is because the synthetic pictures provided

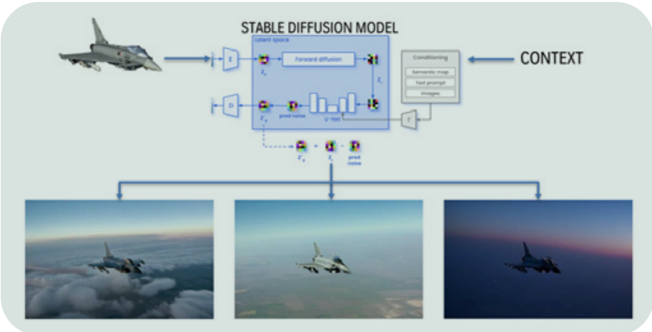
9-Synthetic image generated by an Image Generator

by image generators, although being very detailed and accurate, show a lack of the basic realism with which the deep learning models shall be properly trained. Such a big issue makes this approach inapplicable.

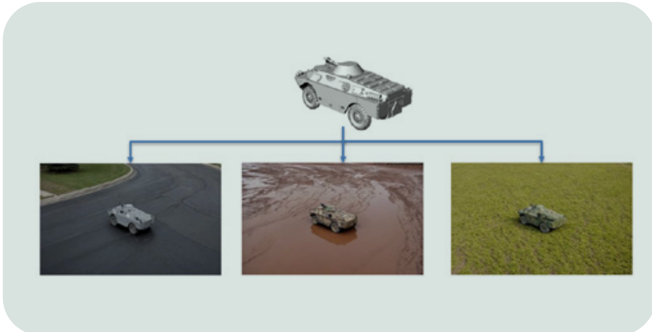
The real question is whether it is possible to add realism to the synthetic pictures generated by Image Generators. In the latest years, the Generative AI has provided us with impressive tools that enable to generate extraordinary contents. The Stable Diffusion Models are an example of state-of-the-art Generative AI capable of creating absolutely new pictures by starting from a textual statement (called prompt), that briefly describes the content of the image the user wants to obtain as the final output. By adapting this architecture to process synthetic pictures instead of generating images from scratch, it is possible to add much-needed realism to the input pictures, which makes them nearly indistinguishable from real images.

This technique allows generating huge datasets of samples containing thousands of subjects immerse in different environment conditions, provided with a level of realism that is very close to real scenarios.
The aim is to use such datasets as the input to train Deep Learning Models, to avoid performance drops when the Neural Network is used in the real world.

Figure 10 and Figure 11 show examples of added realism to synthetic pictures given as the input to the Generative Model. The proposed approach provides a great support to Sustainability, because it is usable and useful without any need to spend significant amounts of field trials, thus saving time and money, and drastically reducing the impact on the environment.



*10-The process used to increase realism of a 3D model: the Generative AI (Stable Diffusion Model in this case) receives the object (on the left) as the input and a list of the contexts (on the right) needed to guide the generation of the pictures.
On the bottom, examples of some results obtained as the output*



11-Another example of three realistic pictures generated by AI (images on the bottom) starting from a 3D model of reference at the top)

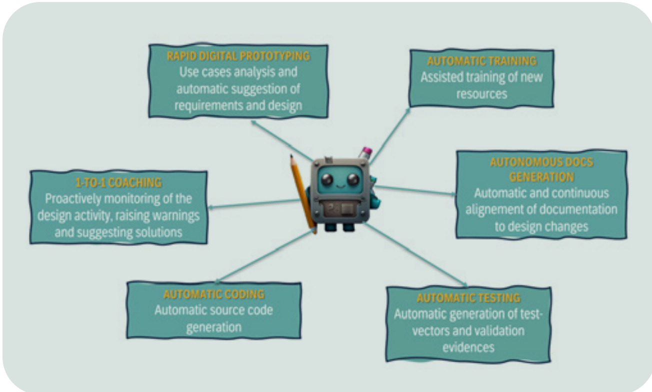
USE CASE 2: Virtual Assistants based on Large Language Models

Digital Engineering affects every phase of the product lifecycle, from design to delivery, involving customer support activities as well. In this frame, Artificial Intelligence can provide a remarkable help to support, improve and speed up design, and development activities, by making available cutting-edge methods and tools capable of actively collaborating with human engineers.
The technology supporting this approach is based on Large Language Models (LLMs). LLMs are advanced Artificial Intelligence systems trained on vast amounts of textual data with the aim of processing, understanding, and generating human language. These models make use of deep learning techniques, specifically transformers architectures and attention mechanisms, to process the input they receive, understanding contextual relationships in text, and generating human-like responses. The potential application of these models is theoretically unlimited and can be summarized in content creation, data analysis, real-time translation, customer service, automatic software coding, educational tools, etc.
When trained on specific domains, LLMs can be used to build Domain-Expert Virtual Assistants able to offer innovative capabilities that will change the way engineers approach their work, by enabling them to focus on the noble components of the activity (e.g. the problem solving), while automating the less valuable part of their work. More in detail, such assistants can be programmed to actively support engineers by providing them with the following capabilities (Figure 12):

- *Rapid Digital Prototyping*
  By processing use-cases, the Digital Virtual Assistants could automatically generate initial design concepts, helping engineers brainstorming, and exploring the best design approaches. They could also automatically translate use-cases to specifications and preliminary design already compliant to requirement definition rules chosen for the project.
- *1-to-1 Coaching*
  The Digital Virtual Assistants proactively monitor the design activity of human experts, to suggest improvements and produce alerts when detecting errors or non-conformities with respect to adopted standards, guidelines and regulations. They can also be queried, in real-time, by human experts, about particular regulations, standards or lessons learnt from previous projects, thus preventing the users from wasting time in searching amongst hundreds of documents.
- *Support to Software Development*
  The Digital Virtual Assistants is used to automatically generate source code in software development, starting from the requirements or the model-based design. They can also provide refactoring and debugging activities, or produce automatic translation among different programming languages.

- *Support to Testing and Verification Activities*
  The Digital Virtual Assistants automatically generates test vectors and produce validation evidences to be used in a given certification process.
- *Autonomous Generation of Documentation*
  The Digital Virtual Assistants automatically generates requirements, design descriptions, and test documentation. They could also monitor design changes during the development process, to automatically align documentation to changes applied to the project.
- *Automatic Training*
  The Digital Virtual Assistants monitors the training activities of human resources, to validate their activities and to propose a personalized training plan customized on the trainee skills.

In this section, we have analysed the use of Domain-Expert Virtual Assistants to support engineering activities, but they could be successfully applied also to support all the business processes that require the application of rules and regulations, or to speed up all the repetitive and time-consuming activities, that typically affect every company function.



12-Some examples of capabilities provided by a Domain-Expert Virtual Assistant

CONCLUSIONS

This paper has presented an overview of the Twin Transition, the so-called Blue (Digital) and Green (Sustainable) Transformation, and has illustrated how Leonardo Electronics Division is interpreting it.

We started with a big picture of the Digital Transformation, described by the DT Taxonomy, with the aim to organize digital transformation in products and processes. Then, we have analysed the twin transition, with particular focus on how Digital Transformation works as the enabler for Sustainability, especially for the decarbonization process.

Next, the design, development and service of a digital product, and the digital factory, from two points of view, with their impact on Sustainability have been described. We have then talked about Digital Transformation having in mind Sustainability with its golden rules. The Morpheus XR use case has been presented to describe how product virtualization can support Sustainability, exploiting a new way maintenance technicians can be trained. Finally, taking into account its predominant role, the impact of the AI based technology has been treated, by means of two use cases, to support and improve Sustainability.

ACKNOWLEDGMENTS

We thank all the Components of the Digital Transformation and Sustainability Teams of Leonardo Electronics Division and in particular Domenica Tabarrini, Elvio Toniutti and Giuseppe Pagnotta, Walter Matta, Daniela Spinosa, and Roberta Colombari.

Caterina Rapisarda: caterina.rapisarda@leonardo.com
Christian Giusti: christian.giusti@leonardo.com
Mario Lombardo: mario.lombardo@leonardo.com
Michele D'Urso: michele.durso@leonardo.com
Paolo Grumelli: paolo.grumelli@leonardo.com
Roberto Lalli: roberto.lalli@leonardo.com
Salvatore Musto: salvatore.musto@leonardo.com
Stefano Pagliai: stefano.pagliai@leonardo.com
Marta Cordoni: marta.cordoni@leonardo.com

REFERENCES

[1] The European House - Ambrosetti (Partner ATOS) – "Verso una net zero society – Tecnologie e strategie digitali per un mondo a emissioni zero", Ottobre 2021

Transforming Defence: Leonardo’s Digital-First Journey to Shape the Future of National Security

Simon Harwood, Gareth Hetheridge, Francesco Rogo, Max Wigley

Leonardo - Corporate

The Defence Industrial Base must transform to remain relevant and practical in an era of rapid technological advancement and evolving security challenges. This journal explores Leonardo’s ambitious journey to becoming a Digital Enterprise, guided by a bold “Digital First” mindset. By embracing advanced technologies, fostering international collaboration, and nurturing a culture of innovation, Leonardo exemplifies how adaptability and vision are essential for shaping the future of National Security. This paper delves into the strategic frameworks, technological advancements, and cultural shifts underpinning this transformation, offering insights into how Leonardo continues to lead in the ever-changing aerospace and defence landscape.

STRATEGIC FRAMEWORKS

Strategic Vision for A Digital Future

Leonardo’s 2024–2028 Industrial Plan signifies the company’s transformation into a Digital Enterprise, guided by a Digital First mindset. This strategy emphasises digital solutions as the foundation for innovation and operational excellence. Within this global and broader digital enabler strategy, Leonardo UK employs a data trinity approach to facilitate this transformation, focusing on how data can be exploited for: internal enterprise benefits, customer availability support, and direct mission enablement. This enhances the OODA loop (Observe, Orient, Decide, Act), allowing for faster decision-making to enable advantage, in each of these three aspects. Leonardo ensures agility and technological superiority in an evolving UK defence landscape through this methodology [1][3].

The company’s commitment to innovation is reflected in its significant investment in research and development (R&D). The report indicates that in its second domestic market Leonardo R&D expenditure in the UK has more than doubled since 2018, reaching nearly £500 million in 2023. This investment highlights the company’s dedication to advancing digital technologies and maintaining a competitive edge in defence [5].

Expanding The Framework of National Security

The evolving definition of national security requires the integration of conventional defence with areas such as Open-Source Intelligence (OSINT), cybersecurity, space control, energy security, and predictive analytics. Leonardo’s investment in artificial intelligence (AI), high-performance computing, and big data analytics positions the company to address offensive and defensive requirements effectively. Initiatives like the Global Combat Air Programme (GCAP) exemplify this vision, showcasing a connected ecosystem of sixth-generation air superiority that features advanced platforms supported by autonomous systems and “Adjunct Collaborative Platforms.”

AI is central to this framework as it enhances decision-making capabilities and improves operational efficiencies. Leonardo has placed AI directly in the hands of war fighters, allowing military operations to become more informed, effective, and responsive to real-time threats. This includes developing AI-driven systems that enhance situational awareness, optimise resource allocation, and mitigate operational risks.

Additionally, Leonardo's commitment to AI assurance ensures these systems are reliable, ethical, and effective. It addresses specific threats to AI technology while safeguarding its application in high-stakes environments. These initiatives underscore Leonardo's leadership in integrating advanced technologies to reshape the several national security landscapes it serves to.

Global connectivity remains a cornerstone of Leonardo's approach, ensuring interoperability and seamless communication across strategic domains — air, land, sea, cyber, and space. The digital backbone supports these efforts, providing a modular, secure infrastructure that integrates processes and facilitates real-time data sharing. This system ensures readiness and adaptability in increasingly contested and complex operational environments [2].

Collaboration Across Boundaries

The Digital Forge, Leonardo's secure innovation environment, facilitates collaboration with SMEs, academia, and defence partners, fostering cross-boundary partnerships that amplify creativity and problem-solving. A prime example of international cooperation is the Data Highway, a secure link between the Genoa-based Da Vinci HPC and the UK's Azure Secure Public Cloud. This infrastructure provided seamless data sharing and joint development was operational within four weeks, setting a precedent for replicability across other high-priority programmes and enabling global partnerships that leverage cutting-edge technologies across geographies.

These initiatives align closely with the "Putting AI into the Hands of the War fighter" conference held in October 2024, which brought together over 130 participants, including representatives from Leonardo, the UK Ministry of Defence, the Defence Science and Technology Laboratory, SMEs, and academia. This event underscores how cross-sector collaboration drives the development of advanced AI solutions, accelerating innovation while ensuring alignment with national and global defence priorities. The collaborative environment promotes the co-creation of AI technologies tailored to specific mission needs, guaranteeing that solutions are scalable, interoperable, and responsive to dynamic operational requirements. This ecosystem exemplifies the power of leveraging diverse expertise to tackle complex challenges effectively.

The New Oxford Economics Report [5] highlights Leonardo's extensive engagement with the UK supply chain. Leonardo spends approximately £1 billion annually with nearly 1,700 companies, 75% of which are small and medium-sized enterprises (SMEs). This collaboration fosters innovation and supports the broader defence ecosystem, aligning with Leonardo's strategy of cross-boundary partnerships.

TECHNOLOGICAL ADVANCEMENTS

The Digital Continuum

Becoming Digital First extends beyond technology adoption; it requires embedding experiential learning and innovation into the organisation's DNA. The Digital Continuum bridges the gap between research and production, leveraging advanced AI, simulation and cloud-based platforms to test and refine technologies efficiently. Rapid experimental feedback loops fuel innovation, allowing Leonardo to "fail fast" without incurring significant costs. By reusing code and ideas across divisions and cross-geographies, the company harnesses collective ingenuity to deliver groundbreaking solutions [2]. One key initiative involved establishing a secure, connected data environment for global collaboration.

With meticulous planning, this initiative took 4 weeks to implement, encompassing connectivity, security controls, and a functional environment. The data platform was deployed in just 4 hours, leveraging two applications, dummy data, and existing run books with infrastructure as code. This success was made possible through collaboration between Leonardo's global teams and partner ecosystem.

By comparison, deploying a similar platform through traditional means was estimated to cost over £1 million and take 12 months. However, the reuse of existing corporate investments in both the Da Vinci HPC and the UK Secure Public Cloud, and re-used of of software assets reduced costs to approximately £20,000, exemplifying the efficiency and scalability of Leonardo's Digital Forge, a cloud-based innovation capability for experimental design-led concepting. The platform now provides a replicable model to support critical programmes and integrate advancements like Generative AI (Gen AI) capabilities developed for Helicopters and Aircrafts programmes in Italy.

Cloud-Driven Innovation

Modern cloud platforms are the backbone of Leonardo's digital transformation, enabling agility and scalability. These platforms (a hybrid framework of secure on premise and certified external public providers) allow teams to create representative environments rapidly, test hypotheses, and iterate on designs with minimal risk. Leonardo's Digital Forge enabled the deployment of a data-lakes and big data analytics environments in a few hours, democratising the access to such digital capabilities for every business function leveraging reusable assets to drive efficiency and cost savings. This approach accelerates innovation and ensures scalable solutions across multiple domains and programmes [2].

The Role of Artificial Intelligence and Machine Learning

AI and machine learning (ML) technologies are crucial in Leonardo's efforts to future-proof its operations by optimising workflows and unlocking new possibilities in manufacturing, for commercial and defence applications. These technologies enable predictive analytics and systems autonomy, improving operational efficiency and helping Leonardo remains competitive in an industry characterised by technological continuous advancements.

The developed systems are designed to augment human decision-making by providing faster, data-driven insights that improve operational outcomes. For instance, AI facilitates more efficient resource allocation and real-time threat analysis, contributing to mission success in contested environments.

Additionally, the importance of AI assurance is highlighted, which involves rigorous testing and the implementation of countermeasures to ensure that AI systems are secure, ethical, and reliable. This proactive approach safeguards against potential vulnerabilities and ensures that AI technologies are robust enough for sensitive defence systems or commercial safety critical applications. By addressing these challenges effectively, Leonardo is a leader in AI's ethical and practical integration.

Global connectivity remains a cornerstone of Leonardo's approach, ensuring interoperability and seamless communication across strategic domains — air, land, sea, cyber, and space. The digital backbone supports these efforts, providing a modular, secure infrastructure that integrates processes and facilitates real-time data sharing. This system ensures readiness and adaptability in increasingly contested and complex operational environments [2].

CULTURAL SHIFTS

Cultural Transformation: Embracing Digital First

Leonardo is undergoing a significant cultural shift to embrace a Digital-First mindset. The organisation focuses on fostering transparency, adaptability, and data-driven decision-making across all levels. Leadership plays a crucial role in this transformation, driving initiatives that ensure every employee contributes to and benefits from this digital evolution.

In the UK for example, recognising that its over 8,000 UK-based employees are central to its high-tech operations, Leonardo is enhancing efficiency by streamlining processes and automating routine tasks.

These improvements allow employees to focus on high-value activities such as innovation and problem-solving. For example, implementing a common data environment has significantly reduced the time required for critical tasks, such as cutting radar test cycles from several days to just a few hours and reducing analysis tasks from four hours to 30 seconds. These gains underscore the organisation's commitment to empowering its workforce while enhancing productivity [1][2].
Leonardo has invested heavily in reskilling and training programs to equip its employees with the digital competencies needed for this transformation. The Training Academies employ advanced tools such as augmented reality, artificial intelligence, and Live-Virtual-Constructive (LVC) learning environments. These programs provide immersive training experiences, focusing on lifelong learning and preparing employees to oversee and implement digital transformation processes. Moreover, these initiatives are extended to external end-users, reinforcing Leonardo's role as a global innovator [2][3].
Additionally, Leonardo's participation in the Alliance for Strategic Skills addressing Emerging Technologies in Defence (ASSETs+) highlights its dedication to fostering technological and digital skills. This European-wide partnership, involving universities and industry stakeholders and funded by European Commission joint effort, aims to enhance the defence sector's competitiveness by preparing a workforce equipped to meet the demands of emerging technologies [3].
Through these comprehensive initiatives, Leonardo is creating a workforce adept at using digital tools, capable of driving innovation and ensuring the company's sustained leadership in the aerospace and defence sectors. This cultural transformation is a testament to Leonardo's commitment to thriving in the digital age and ensuring long-term success, becoming an attractive company of choice in the EMEA defence industrial base.

Measuring Success and Looking Ahead

Key performance indicators, including time-to-market reductions, cost savings, and employee engagement, ensure that Leonardo effectively tracks its digital transformation. The company's roadmap includes leveraging emerging technologies such as quantum computing, autonomous systems, meta-materials, and advanced communication networks. These innovations will solidify Leonardo's position as a global leader in aerospace and defence while contributing to the broader goals of national security and sustainability [1].

CONCLUSIONS

Leonardo's transformation into a Digital Enterprise exemplifies the critical role of innovation, adaptability, and collaboration in reshaping a digital-first mindset. By adopting it the company has not only modernised its operations but also redefined how defence organisations must evolve to address the complex and dynamic security challenges of the 21st century.
Leonardo has demonstrated how technology can drive operational excellence through significant R&D investments, the integration of advanced technologies like artificial intelligence and machine learning, and the deployment of scalable digital platforms. Initiatives such as the Digital Forge, the Data Highway, the High Performance Computing journey and the deployment of rapid, cost-effective data platforms showcase the company's ability to innovate at pace while fostering cross-sector collaboration. These efforts ensure that Leonardo meets today's demands and lays a robust foundation for future defence programmes, including FCAS/GCAP and the broader application of GenAI capabilities.
The company's commitment to AI assurance, workforce reskilling, and fostering a culture of transparency and data-driven decision-making underlines its leadership in navigating digital transformation's ethical and practical challenges. Additionally, Leonardo's engagement with SMEs and academia strengthens the broader defence ecosystem, reinforcing its role as a cornerstone of the UK's industrial and economic landscape.
As Leonardo looks to the future, the digital backbone it has built, encompassing cloud platforms, AI technologies, and global connectivity, will continue to drive its ability to innovate and respond to the evolving demands of national and international security. By embracing transformation at every level, Leonardo remains a leader in aerospace and defence and a model for how organisations can leverage technology to create sustainable, impactful change.
This journey underscores that the future of defence is not just about technology but vision, collaboration, and the courage to innovate for a safer, more secure world.

Gareth Hetheridge: gareth.hetheridge@leonardo.com

REFERENCES

[1] Leonardo. "Industrial Plan 2024–2028: Cumulative Orders of €105 Billion, Total Revenues of €95 Billion, Double-Digit Profitability by 2026 and Doubled FOCF by the End of the Plan." March 12, 2024. [Online]. Available: (leonardo.com).
[2] Leonardo. "Future Factory | Leonardo in the UK." [Online]. Available: (uk.leonardo.com)
[3] Hetheridge, G. "Leonardo UK CIO - Gareth Hetheridge's Cloud Platform Enables Innovation to Lift Off." Diginomica. [Online]. Available: (diginomica.com)
[4] Leonardo. "Putting AI into the Hands of the Warfighter." [Online]. Available: (uk.leonardo.com).
[5] Leonardo. "New Oxford Economics Report shows the growing impact of Leonardo to the UK economy" [Online] Available: (uk.leonardo.com)

Davinci-1: Enabling Infrastructure for a Digital Future

Alessandro Russo, Antonio Sciarappa

Leonardo – Corporate/Strategy and Innovation

Advanced High-Performance Computing (HPC) infrastructures are nowadays essential for enabling digitization of services and production chains, both for industries and for the public sector. In recent years Leonardo has invested huge efforts to become a key player at European level and worldwide in the industrial HPC field. This has led to creation of the first modern supercomputing centre of the company, named Davinci-1. The advanced computing capabilities of Davinci-1 that are Cloud and bare-metal, play a key role in accelerating digital workflows and data analysis, as well as in enabling new capabilities such as Artificial Intelligence. In just a few years, this has resulted in increased competitiveness and has opened a vast range of opportunities, some yet to explore.

INTRODUCTION

The history of computing dates back to thousands of years ago, but just in the last century the digital and electronic computing, which was initially only developed theoretically, found its actual physical realizations. From that point onwards, a whole new world of possibilities opened up that had never been imagined before. This has led to dramatic changes in everyone's lives that only a few decades ago would have sounded as science-fiction. High Performance Computing, although being probably unknown to many, is a key enabler for those innovations we nowadays think of as common and irreplaceable.

HIGH-PERFORMANCE COMPUTING

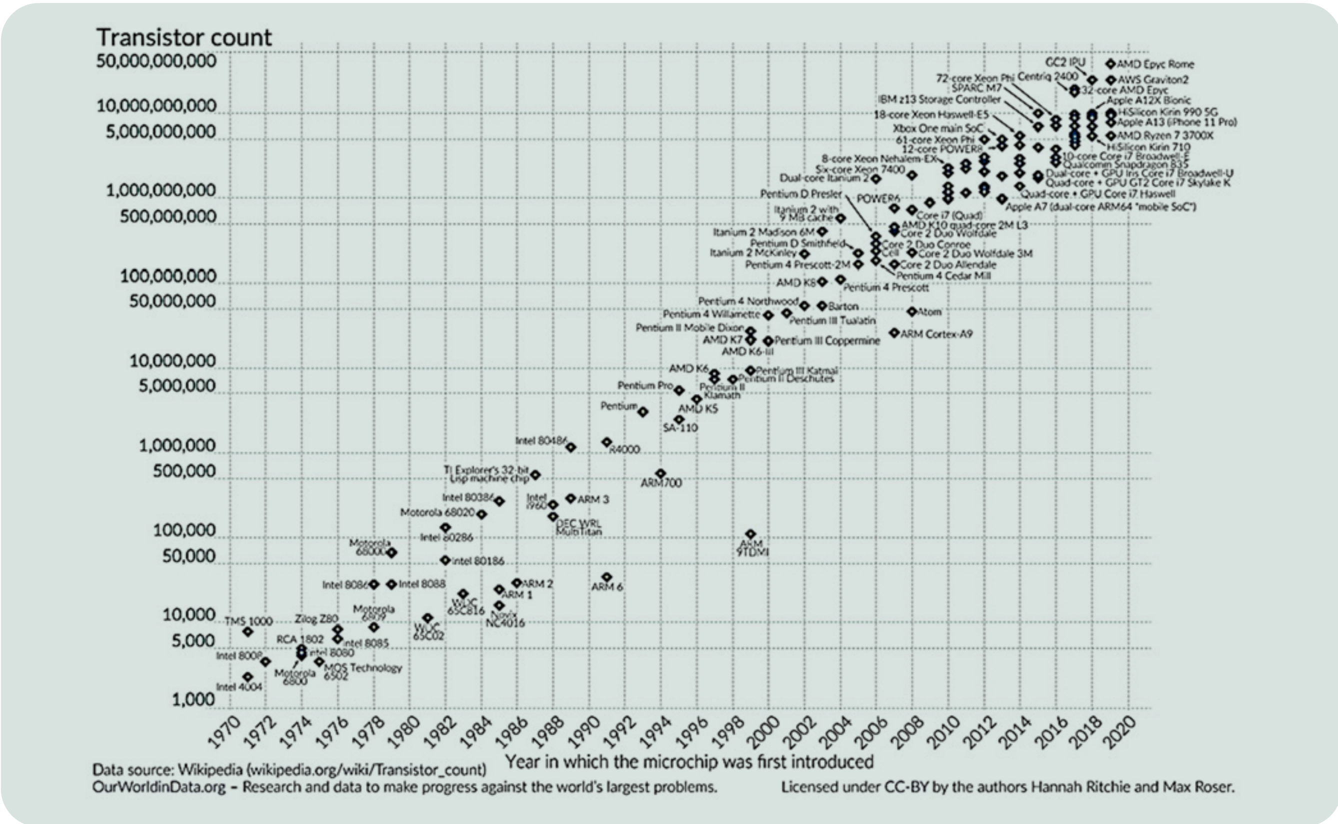
A brief history of HPC

The concept of High-Performance Computing (HPC) has its roots in the early 1960s, with the development of supercomputers capable of performing calculations at speeds that were unprecedented at the time.

The IBM 7030 [1], is generally considered the very earliest high-performance computer in the world. It was developed in 1961 by IBM in collaboration with the Los Alamos National Laboratory. It was the first machine to use transistors rather than vacuum tubes and it was able to reach the theoretical computational peak performance of about 1 MIPS (Million Instructions Per Second). The year 1961 therefore marked a fundamental date and represented a turning point for the development and diffusion of High-Performance Computing infrastructures afterwards. This is evidenced by the creation in 1964 of the first Cray - the CDC 6600 - and by its first real evolution in 1976 with the Cray-1, which could reach the theoretical peak performance of 160 MIPS. Those infrastructures have given rise to what would have become a revolution in the computational field, as at that time achieving such performance values was unexpected and believed to be an impossible feat. The evolution and growth of microprocessors, and more in general of the chip technology itself, has significantly contributed to exponential growth of the supercomputing infrastructures, which has paved the way to growth in performance that was not predictable at all in the sixties/seventies. Till now, such progresses have been well represented by the Moore's Law (Figure 1), an empirical observation according to which the number of transistors in an integrated circuit should double about every two years.

In more recent years, advancement of the chip technology has been improving the performance of individual CPU cores, but it also resulted in huge increase in the number of cores per socket in each single CPU. This has led to new possibilities in parallel computing, whose results are astonishing, if we think of which were the former performance levels we started from. Just as an example, the latest generation of processors can contain up to 256 cores in a single socket. Thus, looking at the recent global trends, it is more and more evident that the growth in performance is continuously increasing.

The advent of GPUs is another fundamental turning point in the history of HPC and in growth of the computing performance. The NVIDIA GeForce256 was marketed in 1999 as the world's first GPUs, initially released for gaming. These GPUs enabled the fast rendering of 3D graphics thanks to their parallel computing capabilities, thus bringing a revolution to the videogame industry [2]. Despite those GPUs were mostly overlooked by the broad tech community at first, after almost a decade they quickly became the driving force of digital evolution. This happened thanks to the first release in 2007 of the CUDA (Compute Unified Device Architecture) Software Development Kit that turned those GPUs into *programmable* ones. It means that, in a sudden, those external graphics devices enabled to introduce new degrees of parallelism in scientific computing, thus providing tremendous acceleration boosts for many compute-intensive applications. This opened a new world of possibilities, also unlocking the vast potential of the Artificial Intelligence world up to generative models of today and beyond.



1 – Moore's Law

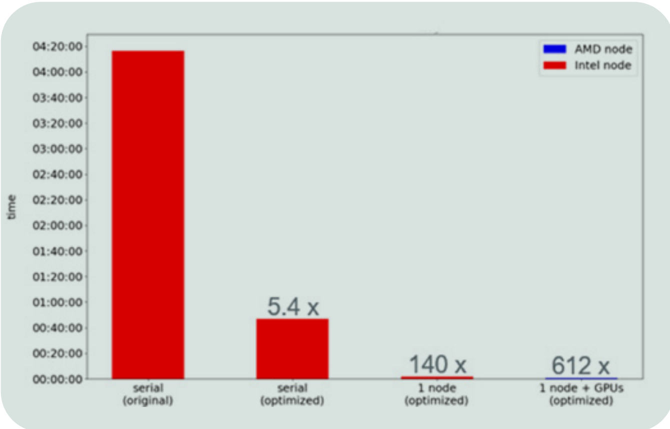
HPC at Leonardo: Davinci-1

However, not only the infrastructure benefits from advances in technology, but also the entire ecosystem that gravitates towards the use of the technology itself. Indeed, in recent years we have been experiencing the affirmation and diffusion of High-Performance Computing infrastructures. Also, many companies are investing in such infrastructures to obtain significant benefits that go ranging from increased digital evolution to optimization of the development costs of their products.

One of such examples is Davinci-1 [3], Leonardo's latest High Performance Computing infrastructure (Figure 2).

The Davinci-1 project started in 2020 by initiative of Roberto Cingolani, who at that time held the position of CTIO in the company and is currently its CEO. Two external consultants, who subsequently joined the Leonardo group, were involved in this project from its very beginning and contributed to realization of the infrastructure.
The Davinci-1 supercomputer was designed and built according to a "futuristic" scheme. After a few years of operation, the choice still demonstrates its validity and effectiveness. The Davinci-1 infrastructure has been designed according to an architectural idea that enables providing pure computing services in a traditional "bare metal" way, as well as a set of new digital services that respond to more modern and different needs, such as Cloud Computing and Artificial Intelligence technologies that in 2020 were already present but had not been fully exploited yet. Such approach enables rapid evolution of many of the digital services that the Leonardo divisions go creating over the time, without any need for using or relying on external support and/or cloud infrastructure providers. The design approach of putting the data at the center of the project, has allowed such an evolution that has turned data into a "source of wealth". This is because the analysis and aggregation of the immense amount of historical data archived and made available from all sources present in the company, supported by dedicated Data Lake infrastructures and Data Analytics models, has enabled the divisions to generate value-added services for their business and their customers.
The possibility of efficiently storing and analyzing large amounts of data ("Big Data"), also designed and delivered as internally managed Cloud services, is however only one of the advantages provided by an infrastructure such as Davinci-1.

2–Davinci-1



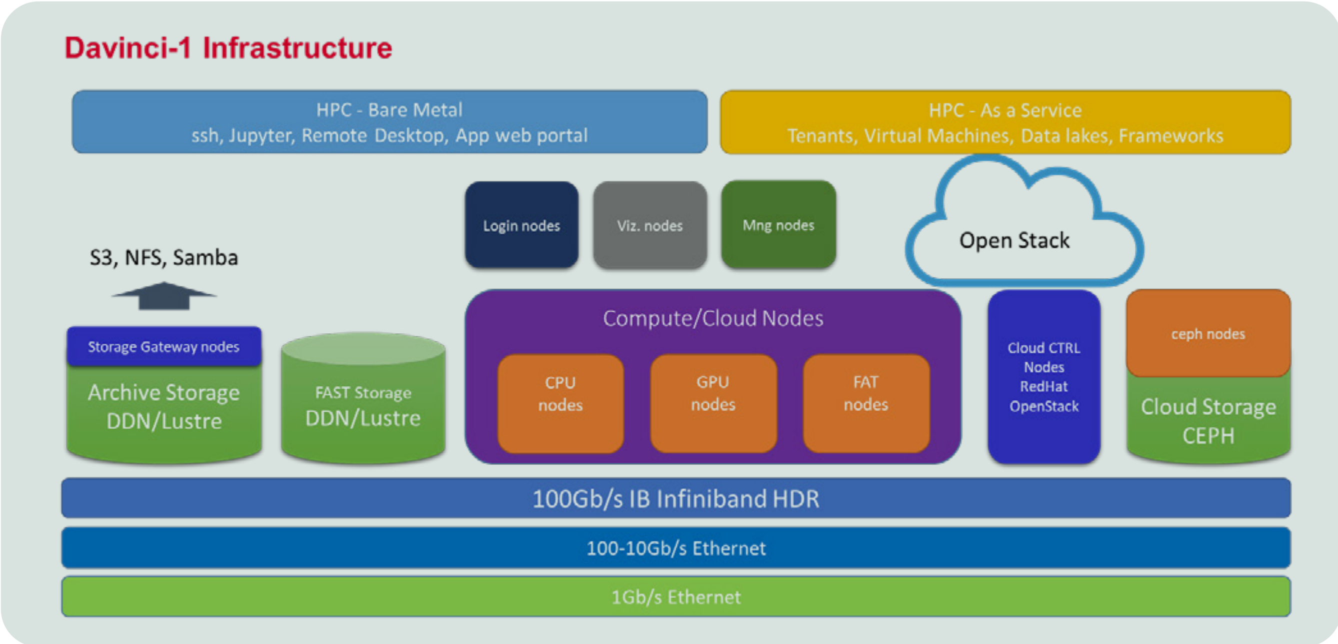
3–Codes acceleration

Its great computing power largely comes from integration of hundreds NVIDIA GPUs of the latest generation, which have enabled to speed-up the calculations for many engineering activities such as Computational Fluid Dynamics. In addition, when combined with advanced parallel programming skills of a dedicated HPC team, it allows to greatly optimize and accelerate proprietary codes, which largely benefit from the porting and modernization work, as they were often based on old technologies. This results in performance boosts by factors of tens on CPUs, or even of hundreds on GPUs, thus significantly reducing the response times (Figure 3).

Davinci-1: the numbers

The Davinci-1 infrastructure was installed in Genova (Torre Fiumara) in 2020. From the architectural point of view, its composition can be schematized as follows:

- About 80 GPU nodes, each equipped with four NVIDIA A100 GPUs and capable of delivering computational power of approximately 43.1 TFLOPS (Trillions Floating-Point Operations per Second);
- About 60 CPU nodes, each capable of delivering computational power of approximately 3.68 TFLOPS;
- Three different network layers of interconnection, which allow the communication between all the components of the infrastructure, its management as well as the parallelization and simultaneous data access via the HDR200 Infiniband technology;
- A total of 25 PB (petabytes, or quadrillions bytes) of high-performance DDN storage with a Luster parallel file system;
- A management component consisting of two distinct parts, which make it possible to provide both traditional HPC computational services and Cloud services by exploiting all the available computing power and storage without distinction.

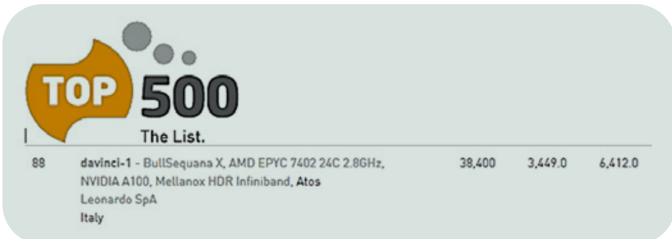


4 – Davinci-1 architecture

The general overview of the Davinci-1 architecture is schematically reported in Figure 4.

The successful architectural design choice of Davinci-1 has allowed Leonardo to quickly become part of the elite of technological companies whose registered infrastructure is in the Top500 list [4]. The Top500 project, launched in 1993, is devoted to list and rank the 500 most powerful supercomputers in the world. The list is updated twice a year, that is in June during the International Supercomputing Conference (ISC) and in November during the Supercomputing Conference (SC). The ranking is established by basing on results obtained on a highly compute-intensive application known as HPL Benchmark [5], that can utilize almost completely the computational capabilities of a supercomputing infrastructure, nearly reaching its theoretical peak performance. Immediately after its activation in late 2020, Davinci-1 ranked 88th worldwide thanks to the 3.45 PFLOPS reached on HPL (Figure 5) and ranked 3rd worldwide when restricting the ranking to the Top500 entities involved in the sector of Aerospace, Defense and Security.

In the years after Davinci-1 installation, further supercomputing infrastructures, much larger and consequently more powerful than it have been released worldwide, which however adopt the same technology it uses. Davinci-1 can be therefore considered as the “pioneer” and this peculiarity allowed it to maintain a dignified 258th position in the Top500 rankings in June 2024 [6]. This is also confirmed by the increase in the use of Davinci-1 at Leonardo’s between 2020 and 2024, which stood at a continuous value of approximately 85%. Such a value demonstrates the solidity of its infrastructure, as for any High-Performance Computing environment it normally stands at a maximum peak of 75%.



5 – Davinci-1 Top500 ranking (November 2020)

Davinci-1 for the Digital Continuum

Since its installation in late 2020 Davinci-1 has quickly become a key asset for the company, leading to a digital revolution that is spreading more and more. A first example of this transformation are the new digital capabilities available to support the entire lifecycle of Leonardo services and products, such as helicopters.

To begin with, in the very early phases of product design the parallel computing capabilities of Davinci-1 can be used to speed up the process of identifying the best configuration of a product, by running multiple simulations at once to tune the design parameters (“design driven by simulation”).

In a subsequent validation phase, high computational power is necessary to run full simulations of the physical behaviour of the system, based on Digital Twin techniques. In many cases such techniques are so advanced that allow to certificate products by remaining purely in the digital domain ("design validated by simulation"), without having the need to physically build a prototype, thus saving enormous amounts of time, effort, money, and energy. In the sales phase, realistic and detailed 3D graphic visualization and rendering of the product, achieved thanks to the advanced GPUs hosted on HPC, can give potential customers a very precise understanding of what the final product will look like and what additional customizations or modifications may be needed. During the operational life phase, data collected from different kind of sensors can be stored into Data Lakes that allow to view and query data relative to the state of the product; when integrated with Big Data Analytics and Artificial Intelligence techniques, these can provide new digital services for the physical object such as health monitoring and predictive maintenance, suggesting corrective actions that can expand its operational lifetime. Finally, even after their dismissal, data collected on Leonardo products may still be kept on such Data Lakes and used for post-sales analysis, which can guide further improvements on the line of products. As enablers of all such digitization capabilities, Davinci-1 and similar infrastructures are therefore becoming more and more essential in the lifetime of physical products, from their initial design to end-of-life, making them fully integrated in the Digital Continuum.

In addition to supporting and accelerating manufacturing, Davinci-1's powerful computing capabilities make it possible to enable new services, such as deployment of AI solutions like chatbots on-premises. This allows organizations to maintain control and security over their data, by offering a 'sovereign' solution. Davinci-1 also acts as a technological and skills accelerator, allowing its users and new generations of researchers to use this infrastructure as a training ground for innovation. In fact the Leonardo Innovation Labs researchers, through this technological platform, are projecting themselves towards a continuous advanced development of solutions that create the basis for the business activities of the divisions. Examples are the IT and Physical security sector, which are benefiting from research activities such as encryption, or image recognition from ground of space devices, that through advanced computational capacity is able to provide a response in a short time, essential in cases such as safeguarding the territory and its environment.

The whole digital world is constantly evolving, and such a fast-paced universe needs to be ridden through the continuous learning of new technologies and their applications, which can only and exclusively be carried out through an enabling infrastructure such as a HPC.

CONCLUSIONS

Since its very beginning, progresses in digitization have been tightly related to the evolution of computational capabilities, which has found its most concrete realization in the upbringing of increasingly more powerful supercomputing infrastructures that nowadays reach the exaflops scale. The global need for compute power is becoming more and more evident by looking at the huge number of computations required by recent large models for Artificial Intelligence. These, among other consequences, are driving increasing demands to Cloud Computing providers such as Microsoft, Google and Amazon and are leading to construction of new HPC centres by Big Tech industries. It is therefore clear that companies that want to stay at the forefront of digital innovation, now and in the long-term future, cannot neglect supercomputing. Being well aware of such a changing world, Leonardo has successfully demonstrated its capabilities in this sector by taking its first important steps with Davinci-1, which is only the beginning of a long and exciting road ahead.

Antonio Sciarappa: antonio.sciarappa@leonardo.com

REFERENCES

[1] "The IBM 7030, aka Stretch" [Online]: https://www.ibm.com/history/stretch
[2] "Game-Changer: How the World's First GPU Leveled Up Gaming and Ignited the AI Era" [Online]: https://blogs.nvidia.com/blog/first-gpu-gaming-ai
[3] "Supercomputer Davinci-1" [Online]: https://www.leonardo.com/en/innovation-technology/davinci-1
[4] The Top500 website [Online]. Available: https://top500.org/
[5] "HPL Benchmark" [Online]: https://icl.utk.edu/hpl/
[6] https://www.top500.org/lists/top500/list/2024/06/?page=3

Addressing the Challenges of Hypersonic Flows with Numerical Simulations

Joel Guerrero[1], Eric Segalerba[1], Tony Di Fabbio[1], Gian Marco Zampa[1], Ivan Spisso[1], Federico Piscaglia[2]

[1]Leonardo – Corporate/Strategy and Innovation, [2]Politecnico di Milano - Dept. of Aerospace Science and Technology

The supersonic flow above Mach number 5 is typically known as the hypersonic flow regime, although there is no clear definition of the starting point for the hypersonic flow regime. Typical hypersonic applications are hypersonic cruise vehicles, launch vehicles, and re-entry atmospheric vehicles/capsules. The flow surrounding a vehicle flying at hypersonic speed exhibits the interaction of many physical phenomena, such as strong shock waves, high temperatures resulting in gas dissociation and ionization, radiation, radio and telemetry blackout, low-density effects, wall catalysis, and wall ablation. Therefore, a multidisciplinary approach is needed to address those problems. This paper briefly outlines the technologies adopted and the activities conducted at Leonardo Labs to address such problems from the point of view of numerical simulations of the continuum.

INTRODUCTION

In aerodynamics, a conventional rule of thumb defines hypersonic flows as those flows whose Mach number is greater than 5. However, it is important to note that there is no clear definition about the starting speed for the hypersonic flow regime. Rather, the hypersonic flow is better defined as that regime at which some physical flow phenomena, such as thin shock layer, high-temperature effects, viscous interactions, radiation effects, and surface reactions, become progressively more important as the Mach number increases to higher values [1]-[3]. In some cases, one or more of these phenomena might become important above Mach 3, whereas in other cases they may not be compelling until Mach 7 or higher [1][2]. Typical hypersonic applications include missiles, sounding rockets, small satellite launch vehicles (SSLV), highly reliable reusable launch systems, hypersonic cruise vehicles, scramjet propulsion systems, and atmospheric re-entry vehicles/capsules. Other applications that in recent years have seen increased interest in the Aerospace and Defence sector are: hypersonic platforms for countering hypersonic threats, hypersonic cruise missiles (HCM), hypersonic glide vehicles (HGV), and tracking and detection of hypersonic threats [4].

Peer-reviewed publications with hypersonic subjects have seen significant growth, as shown in Figure 1, which reflects the increasing interest and advancements in hypersonic technology. Since the term first appeared in the early 1940s, over 26,300 papers have been published, by now. In Figure 2, their distribution by top publishing countries shows that the majority of those publications come from China and the USA, which highlights their leading roles in hypersonic research [5]. Hypersonic research is crucial for Europe and Italy, as it positions them at the forefront of technological innovation and defence capabilities. The European Space Agency (ESA) is actively working on hypersonic vehicles, which could revolutionize the air travel and space exploration by significantly reducing travel time and fuel consumption. This research is vital for maintaining Europe's competitive edge in the aerospace technology. For Leonardo, the hypersonic research is of strategic importance, as it enables the development of cutting-edge technologies that can be integrated into civilian and military applications. By investing in hypersonic research, Leonardo can enhance its product offerings, improve national security, and contribute to Italy's technological sovereignty. Hypersonic flow simulations are among the most challenging and difficult areas of computational fluid dynamics (CFD) and multi-physics simulations (MPS).

The CFD Vision 2030 Integrating Committee [6] has named the hypersonic modelling and simulation as one of the grand challenges [7][8] to be tackled to reach the objectives as outlined in the NASA report "CFD vision 2030 study: a path to revolutionary computational aerosciences" [8].
The design of hypersonic vehicles today greatly depends on using the CFD and the MPS. The primary reason is the lack of flight data and of experimental ground test facilities that can simultaneously simulate the Mach numbers, the Reynolds numbers, and the high-temperature levels associated with hypersonic flight [8]-[10]. For such flow conditions, numerical simulations are the one primary source of data for the hypersonic flight regime when the ground/flight testing is limited or does not exist at all. In many cases, wind tunnel data is used only to anchor the CFD data at a few test points to provide confidence in the CFD database [8].
To understand difficulties and complexities of the simulating hypersonic flows, let's look at the governing equations of fluid dynamics. In its most general form, the fluid motion is governed by the time-dependent three-dimensional compressible Navier-Stokes system of equations. For a viscous Newtonian, isotropic fluid in the absence of external forces, mass diffusion, finite-rate chemical reactions, and external heat addition, the conservation form of the Navier-Stokes system of equations in compact differential form and in primitive variable formulation (density ρ, velocity vector u, and total energy e_t) can be written as,

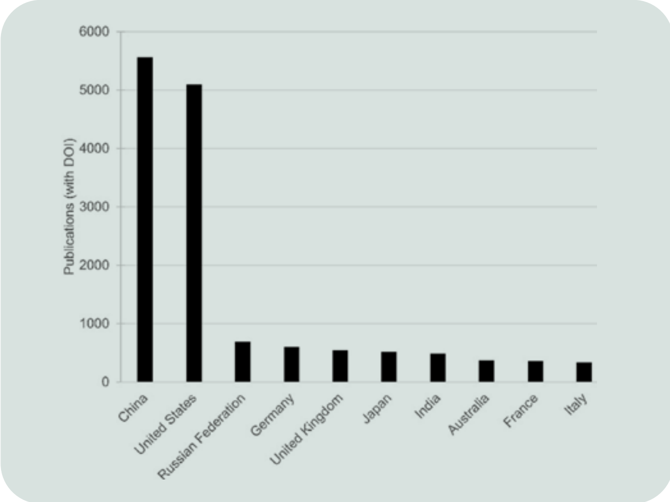
$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\ \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) &= -\nabla p + \nabla \cdot \tau \\ \frac{\partial (\rho e_t)}{\partial t} + \nabla \cdot (\rho e_t \mathbf{u}) &= -\nabla \cdot q - \nabla \cdot (p\mathbf{u}) + \boldsymbol{\tau}{:}\nabla \mathbf{u} \end{aligned} \qquad (1)$$

$$+$$

Additional thermodynamic and transport closure relations

Typically, these equations are numerically approximated by using state-of-the-art CFD solvers based on the assumption that the fluid is a continuum, the perfect gas law applies, and the loads are due to pressure, viscous, and thermal effects. The hypersonic environment is characterized by extreme conditions and complex physical phenomena that are not relevant at lower velocities. For example, at high altitudes and high temperatures (the operating conditions typical to hypersonic vehicles), the continuum assumption of the gas might no longer be valid, as the mean-free path of the gas molecules is on the order of the overall length of the vehicle [9]. Similarly, the other assumptions can lead to additional difficulties. Henceforth, to accurately simulate hypersonic flows, all the flow features and physical phenomena interacting within the hypersonic environment must be considered and adequately modelled.

1-Peer-reviewed publications that contains the word "hypersonic" in their title [5]

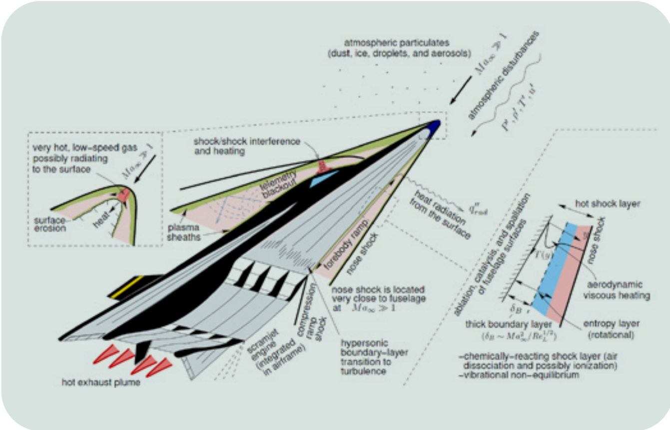


2-Distribution by top publishing countries [5]

Such physical phenomena should be:

- Turbulence and transition to turbulence: The change from smooth to chaotic flow, affecting momentum and heat transfer in high-speed flows.
- Thin shock layer: A thin boundary layer formed by shock waves in supersonic or hypersonic flows, causing rapid pressure, temperature, and density changes.
- Shock waves and boundary layer-shock wave interactions: Interactions between shock waves and boundary layers that affect aerodynamic performance, often causing flow separation and increased drag.
- Low-density flows: Flows at high altitudes or in space with lower molecular density, affecting compressibility and viscosity of the working fluid.
- High-temperature and high-altitude effects:

- Ionization and dissociation of air molecules at high altitudes and temperatures, altering thermodynamic properties during re-entry or high-speed flight.
- Extreme heat transfer: High-speed or re-entry flows causing significant heat transfer to surfaces, due to extreme temperatures.
- Communication and telemetry blackout due to plasma sheath: Ionization during re-entry or in space forms a plasma sheath that temporarily blocks communication signals.
- Thermodynamical characterization of chemically reacting gases: The study of gas reactions at high temperatures, affecting flow properties in combustion chambers or during atmospheric entry.
- Species transport: The movement of chemical species in a flow, influenced by convection, diffusion, and reactions, relevant in reactive high-temperature flows.
- Transport properties of diffusion models: The study of momentum, energy, and mass transfer through diffusion, impacting heat and mass transfer rates in rarefied flows.
- Surface catalysis, ablation, radiation, and others: Surface reactions, material erosion, and energy emission in high-speed flight, critical for vehicle integrity during re-entry [3][11]-[13].



3 – Flow phenomenology around a hypersonic vehicle [14].
(Copyright on the images is held by the contributors. Apart from Fair Use, permission must be sought for any other purpose)

Figure 3 depicts the Fluid-Structure-Thermal-Interaction (FSTI) phenomena encountered in a hypersonic flight [14].

SIMULATION TOOLS FOR THE HYPERSONIC CONTINUUM

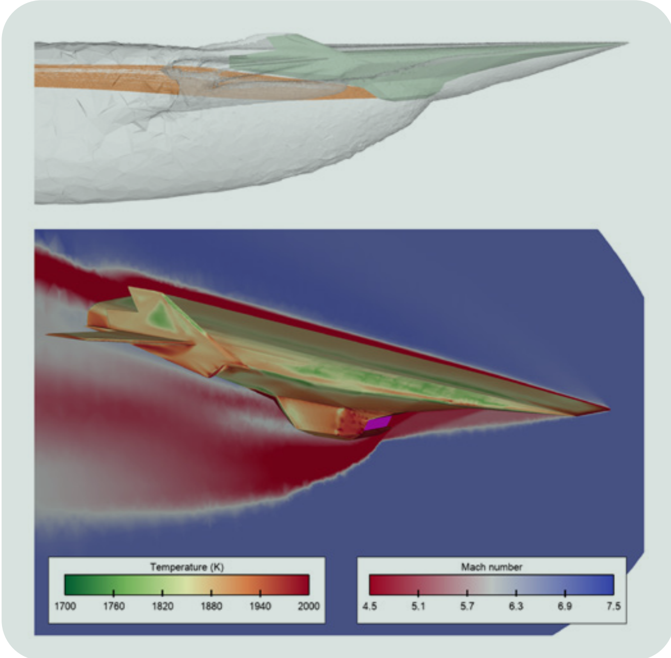
As we stated in the previous section, an important hypothesis when modelling fluid flows by using CFD is that the working fluid is a continuum. When dealing with hypersonic flows and with phenomena related to the hypersonic environment, the current state-of-the-art in CFD focuses on solving the Navier-Stokes equations, in conjunction with turbulence models and chemical physics equations. The latter include the non-equilibrium chemical reactions and internal degrees of excitation (also known as the high-enthalpy non-equilibrium Navier-Stokes equations). Perhaps, the most used non-equilibrium model in CFD is Park's two-temperature model [15]. As in the rarefied domain the continuum hypothesis is no longer valid, different approaches must be considered, such as the semi-empirical methods, the inviscid small disturbance theory, and the Direct Simulation Monte Carlo (DSMC) algorithm [16]. Hereafter, we focus our discussion on using the continuum hypothesis and the tools currently adopted at the Leonardo Labs to address hypersonic flows in the continuum.

Hypersonic aerodynamics paced the development of the CFD since the earliest beginning of numerical simulations. The opposite is true as well, as the impact of the CFD on hypersonic aerodynamics has been greater than on all the other flight regimes (subsonic, transonic, supersonic). This is due mainly to the lack of hypersonic ground test facilities and the high cost and difficulties of conducting flight tests, especially at the extreme ends of the spectrum, where the Mach number is greater than 10, and the stagnation temperatures are high enough to cause substantial chemical dissociation and ionization of the gas. In hypersonic flows, the temperature behind strong shock waves can reach 11000 °K. For comparison, the temperature of surface of the sun is about 5000 °K [1]. One of the most important topics of research in hypersonic aerodynamics is to find a reasonable way of calculating the temperature that is felt by a surface. In place of ground testing facilities and flight tests, the study of hypersonic vehicles must rely heavily on results of the CFD simulations.

At Leonardo Labs, we use commercial and open-source technologies to conduct numerical simulations of hypersonic flows. On the commercial side, we use Ansys Fluent [17], a robust, accurate, stable, highly scalable general-purpose multi-physics solver based on the finite volume method (FVM). That solver features many physical modelling capabilities, including models for turbulence, heat and mass transfer, chemical reactions, combustion, acoustics, high-enthalpy non-equilibrium flows (such as Park's model [15]), radiation, multiphase flows, phase change, electric potential, magnetohydrodynamics and more. On the open-source side, we use OpenFOAM [18], a robust, accurate, stable, scalable solver based on the FVM method that comes with extensive physical modelling capabilities. However, the standard released version does not feature physical models suitable to deal with high-enthalpy non-equilibrium flows.

Thus, in collaboration with the Department of Aerospace Science and Technology (DAER) of the Politecnico di Milano, we have implemented in OpenFOAM the high-enthalpy non-equilibrium modelling capabilities that are similar to those found in Ansys Fluent [19][20]. Additionally, extensive work is being done related to validation and verification and bringing GPGPU (general-purpose computing on graphics processing units) capabilities to OpenFOAM [20][21], being everything included within the LeoFOAM project.

Both multi-physics solvers are available on Leonardo's Davinci-1 (DV1) supercomputer, a key asset that enables large-scale, high-fidelity simulations on both CPU and GPGPU architectures. The use of Davinci-1 as an advanced HPC platform plays a crucial role in enabling and enhancing the research described, providing cutting-edge computational power and the necessary processing capacity to tackle complex scientific and engineering challenges. Figure 4 shows the complex flow field around the NASA experimental unmanned hypersonic aircraft X-43. In the top image of that figure, the Mach cone is visualized by using the numerical Schlieren method (grey iso-surfaces computed using density gradient); the orange streamlines follow the flow coming from the outlet of the Scramjet engine. In the bottom image of the same figure, the temperature contours are visualized on the vehicle's surface, and the Mach number is depicted on the cut-plane. The simulation has been performed by using a simplified geometry of the X-43 vehicle at Mach number equal to 7, altitude equivalent to approximately 24000 m, angle of attack equal to 5 degrees, and the air has been assumed as non-reacting. In the simulation, we have also considered the flow of the scramjet engine, where proper stagnation conditions are imposed in such a way that the thrust of the engine are equal to the total drag of the vehicle. The simulation has been performed using Ansys Fluent in DV1.



4 - Flow about the NASA X-43 hypersonic vehicle

SAMPLE APPLICATION 1. FLOW AROUND A RE-ENTRY CAPSULE AT HYPERSONIC REGIME

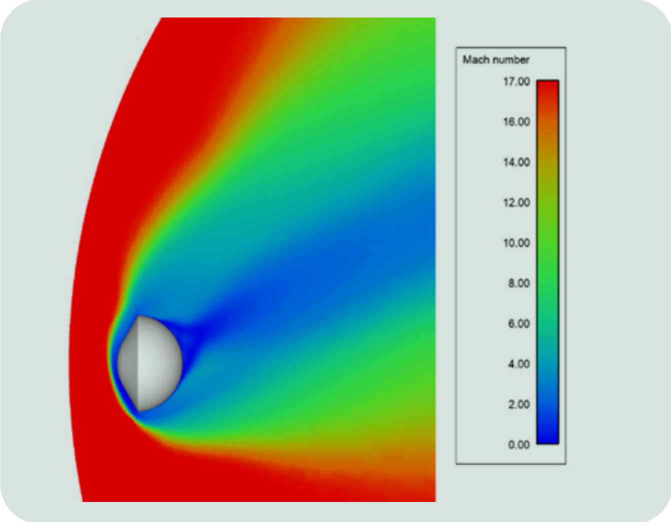
Hereafter, we study the flow around a re-entry capsule at hypersonic speed. The simulated velocity, trajectory, and ambient conditions are representative of such a vehicle as it passes through the Earth's atmosphere at altitude of approximately 50 km. The re-entry capsule is set at angle of attack of 25 degrees, and the free stream Mach number is equal to 17. To conduct this simulation, we use the k-omega SST turbulence model [22] and Park's two-temperature model for high-enthalpy non-equilibrium flows [15]. The simulations are conducted by using the multi-physics solver Ansys Fluent [17] in DV1.

In Figure 5 and Figure 6, we depict the Mach number contours and the temperature contours, respectively. In Figure 7, the shock waves are visualized using numerical Schlieren, and the total temperature is depicted on the capsule surface. These contours provide a detailed view of the aerodynamic and thermal conditions surrounding the vehicle during its hypersonic flight. Moreover, the temperature field can be used as a guide to design the thermal protection system. Extremely high temperatures exist behind the bow shock, which is sufficient to cause dissociation of molecular species and may potentially lead to ionization in the flow field [1].

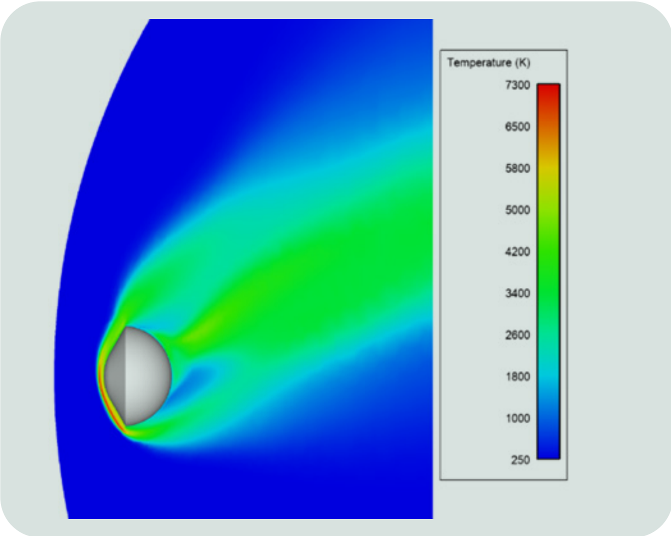
Such high temperatures result from compression of the airflow across the bow shock (shown in Figure 7), which leads to increase in both temperature and pressure in the shock layer. Those high temperatures can break down the molecular bonds of air constituents, such as oxygen and nitrogen, creating free radicals and ions in the post-shock region. The resulting ionization can significantly impact the vehicle's aerothermal characteristics and create complex flow behaviour that must be accurately modelled to design vehicles for optimal performance.

Figure 8 shows the normalized electron number density, which is indicative of the degree of ionization within the flow. Areas with high electron densities are typically associated with regions of significant ionization, which often occur in the shock layer and the boundary layer surrounding the vehicle. The flow becomes highly ionized in these regions that are particularly important to study communication and telemetry blackout phenomena. The ionized air can create a dense plasma sheath around the vehicle, which effectively blocks radio frequency (RF) signals used for communication, thus leading to communication blackout during high-speed atmospheric entry. The extent of ionization and its related electron density are critical factors in determining the duration and severity of communication blackouts, as they directly affect the vehicle's ability to transmit and receive signals. The ability to accurately predict the behaviour of the ionized regions by using CFD tools is therefore essential not only for optimizing aerodynamic and thermal performance but also for designing vehicles whose shape can mitigate the communication blackout phenomenon. CFD simulations enable the detailed modelling of the complex flow field, allowing engineers to identify critical regions where ionization may occur and to assess the potential for communication disruption. By understanding these phenomena, it is possible to design vehicles with features that minimize or control the ionization around key communication surfaces, such as antennas and leading edges, to ensure seamless communications during the critical phases of the hypersonic flight.

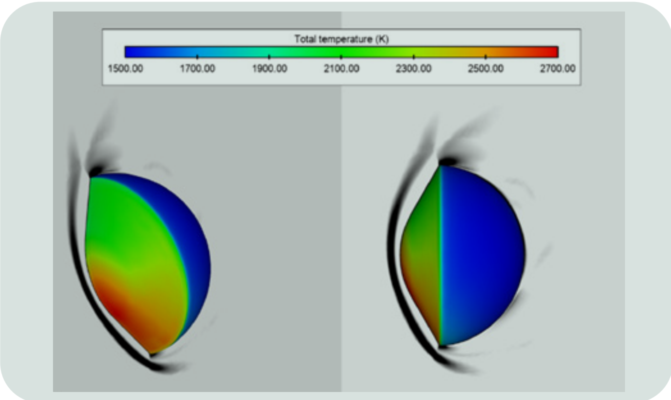
In Figure 9, a comparison between the reacting and non-reacting conditions under similar flow parameters is presented. As observed, the reacting condition predicts a significantly shorter shock standoff distance (sudden increase region) and a lower peak temperature, in comparison to the non-reacting condition. This behaviour can be attributed to the role of chemical reactions in modifying the thermodynamic statuses within the flow field. In a reacting flow, the chemical reactions absorb thermal energy, thus reducing the available heat in the post-shock region. Depending on their nature, these reactions can endothermically consume energy and lower the peak temperature observed in the shock interaction. In contrast, under non-reacting conditions, the flow is governed purely by the conservation of mass, momentum, and energy, without the influence of any chemical processes. This results in higher peak temperature and longer shock standoff distance. Furthermore, the inclusion of chemical reactions alters the thermodynamic statuses of the flow downstream of the shock. The change in composition of the gas due to reaction products, leads to modifications in the specific heat capacity, enthalpy, and other thermodynamic properties, all of them impacting the temperature and pressure profiles behind the shock. This results in a distinctive temperature profile when compared to the non-reacting scenario (refer to Figure 9), where such effects are absent. This comparison underscores the importance of using appropriate physical models to accurately capture the relevant physics of a given system. The presence or absence of chemical reactions significantly influences the shock structure and thermodynamic status of the flow. This demonstrates that neglecting the reaction dynamics can lead to wrong predictions, especially in high-temperature and reactive flow environments. Hence, incorporating reactive models into hypersonic flow simulations is critical to accurately represent the shock behaviour and temperature distribution in reactive flows.



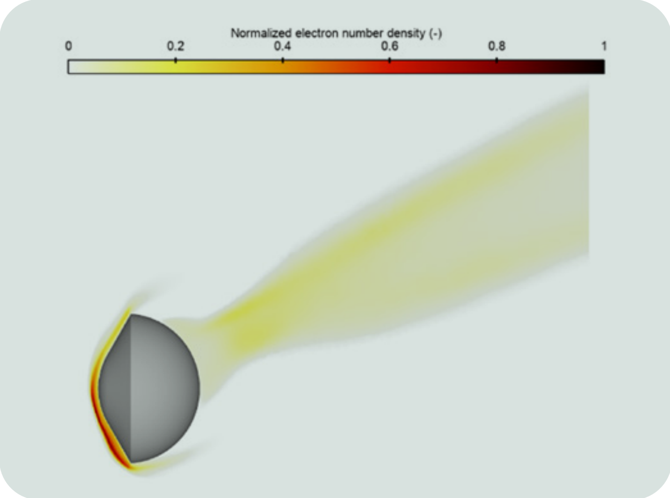
5-Flow about a re-entry capsule. In the image, the Mach number contours are visualized



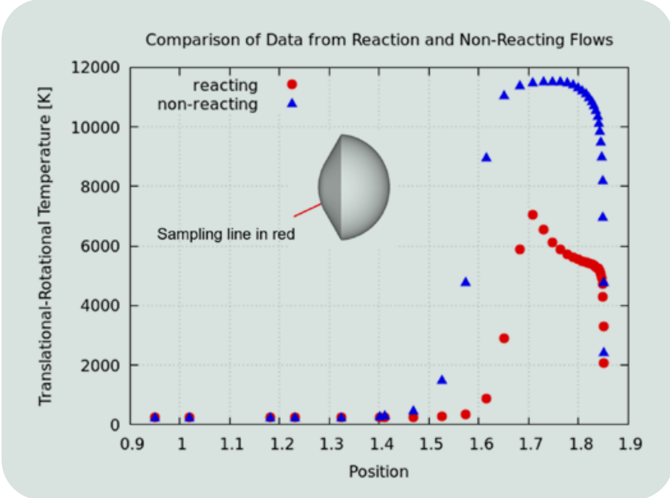
6-Flow about a re-entry capsule. In the image, the temperature contours are visualized



7-Flow about a re-entry capsule. In the image, the bow shock and flow expansion waves around the outer edge of the capsule are visualized using numerical Schlieren (grey scale). The total temperature is depicted on the capsule surface (colour scale)



8 - Flow about a re-entry capsule. The contours of normalized electron number density are depicted in the figure



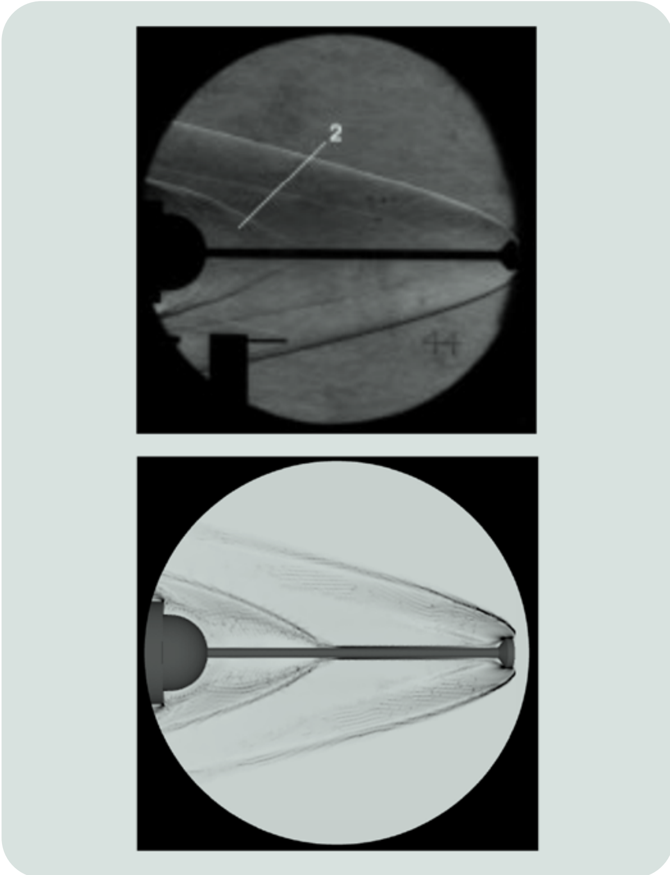
9 - Comparison between the reacting and non-reacting conditions under similar simulation parameters. The translational-rotational temperature is plotted along a line through the shock wave and the surface of the capsule

SAMPLE APPLICATION 2. AEROSPIKE-NOSED VEHICLE AT MACH NUMBER 6

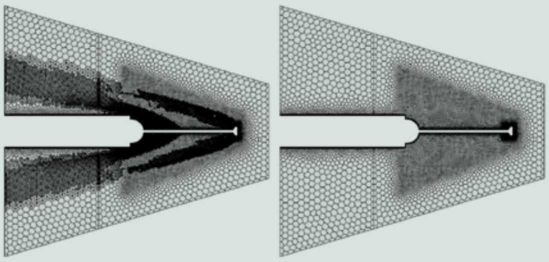
This study is based on the aerospike-protected missile dome experimentally tested at Mach number 6, as reported in reference [23]. The aerospike-nosed vehicle exploits a sting mounted on the nose of the vehicle to offset the shockwave away from the body. This reduces drag, thermal, and structural loads on the vehicle's body. Hereafter, we present a qualitative and quantitative validation of the experimental results discussed in reference [23]. The numerical simulations have been conducted with the open-source multi-physics framework OpenFOAM [18] in DV1.

In Figure 10, we present the shock wave system created by the aerospike-vehicle configuration. As can be seen, the numerical simulations capture the physical behaviour (shock location) very well. Figure 11 shows the use of the Adaptive Mesh Refinement (AMR). This technique is used to increase the density of the mesh in a given region of the numerical domain, so flow features are better resolved. In this case, we used the density gradient as the criterion to trigger the AMR refinement. It is worth mentioning that currently OpenFOAM does not support any AMR on polyhedral meshes; therefore, we used a third-party tool to obtain the new mesh.

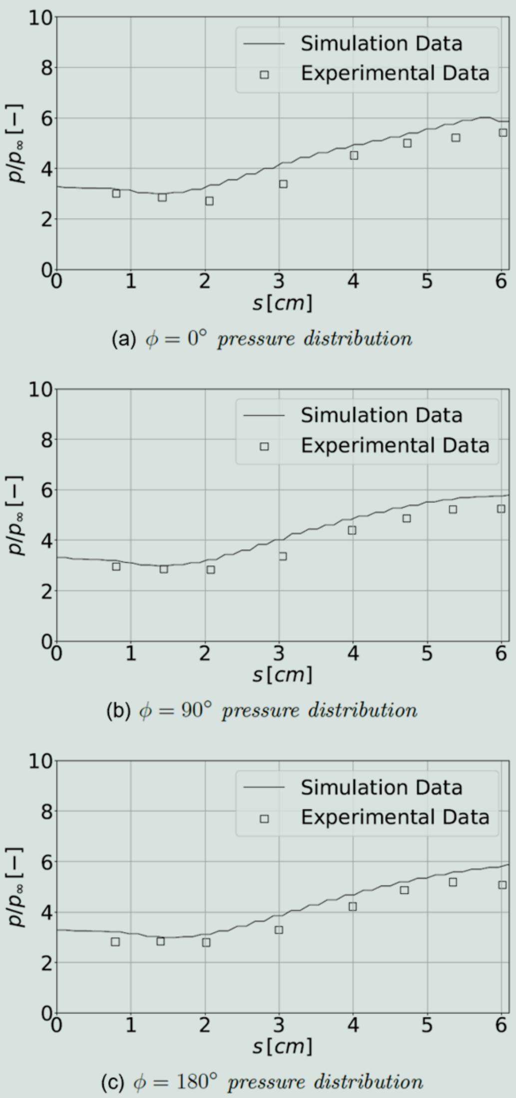
In Figure 12, we depict the pressure distribution measured on the dome of the device at different locations [23]. The numerical predictions match the experimental results relatively well. However, slight deviations can be observed. This might depend on measurement uncertainties not quantified in the experimental tests and on uncertainties present in the numerical simulations, due to mesh resolution, turbulence model, boundary conditions, numerical discretization, and linear solvers tolerance.



10 - Visualization of the shock waves around the aerospike. Top image: Schlieren flow field photograph. In the image, caption 2 indicates aerospike-induced separation region [23]. Bottom image: numerical Schlieren



11-Demonstration of AMR to better capture the shock waves. Right image: the original mesh. Left image: the mesh after AMR



12-Comparison of experimental and numerical pressure distribution measured on the dome of the device (experimental pressure data obtained from reference [23])

CONCLUSIONS AND PERSPECTIVES

The ability to simulate hypersonic flows requires the use of robust, accurate, stable, highly scalable general-purpose multi-physics solvers. In addition to the use of state-of-the-art numerical methods to deal with the highly non-linear physical phenomena encountered in this regime, the use of high-performance computing (HPC) hardware is also a requirement to conduct large-scale simulations needed to properly solve separated flows, use adaptive mesh refinement to resolve critical flow features such as shocks and shear layers, handling complex geometries, accurately compute the aerodynamic loads, in particular heat transfer rate, and solve the most important space and time scales in reasonable times. Moreover, the usual physical models required at lower speed regimes are also required at hypersonic regime, such as the turbulence and transition models. The high temperatures experienced at hypersonic speeds add more complexity to the problem. Therefore, extra models are needed to characterize the equation of state, chemical kinetics (equilibrium and non-equilibrium), thermal status of species, transport properties of diffusion models, surface catalysis, radiation, and others, which makes the simulation of hypersonic flows even more challenging. Furthermore, the limited capacity of the hypersonic aerodynamic community to effectively represent a hypersonic flow in experiments (ground and flight tests), makes the accurate hypersonic CFD predictions even more difficult. This is primarily because of the lack of substantial experimental data that can be used to validate the models and simulations.

To summarize, the hypersonic environment and the design of hypersonic vehicles are some of the most challenging and difficult areas of computational fluid dynamics and multi-physics simulations. These often involve interactions among many disciplines such as aerodynamics, aerothermodynamics, aero-thermo-chemistry, plasma-dynamics, materials science, propulsion, thermal management, guidance-navigation-and-control (GNC), and communication and tracking. Therefore, a multidisciplinary approach must be adopted. All these challenges are currently being tackled by the Digital Twins and Advanced Simulations research group at Leonardo Labs, with the vision of developing accurate multi-physics Digital Twins of hypersonic vehicles.

Joel Enrique Guerrero Rivas: joelenrique.guerrerorivas@leonardo.com

REFERENCES

[1] J. D. Anderson Jr., Hypersonic and High-Temperature Gas Dynamics, Third Edition, AIAA Education Series, 2019.
[2] R. M. Cummings, W. H. Mason, S. A. Morton, D. R. McDaniel, Applied Computational Aerodynamics: A Modern Engineering Approach. Cambridge: Cambridge University Press, 2015.
[3] M. Salas, A Review of Hypersonics Aerodynamics, Aerothermodynamics and Plasmadynamics Activities Within NASA's Fundamental Aeronautics Program, 39th AIAA Thermophysics Conference, 25-28 June 2007, Miami, FL, USA. https://doi.org/10.2514/6.2007-4264
[4] Science & Technology Trends 2023-2043: Across the Physical, Biological, and Information Domains, Volume 1 and Volume 2, NATO Science & Technology Organization, Office of the Chief Scientist, NATO Headquarters, Brussels, Belgium, 2023.
[5] Theofilis, V., Pirozzoli, S. & Martin, P. Special issue on the fluid mechanics of hypersonic flight. Theor. Comput. Fluid Dyn. 36, 1–8 (2022). https://doi.org/10.1007/s00162-022-00605-2
[6] CFD Vision 2030 Integration Committee. https://www.cfd2030.com/. Accessed 22 November 2024.
[7] S. A. Morton, R. M. Cummings, CFD 2030: Hypersonic Modeling & Simulation Grand Challenge, AIAA SciTech Forum, 8-12 January 2024, Orlando, FL, USA. https://arc.aiaa.org/doi/10.2514/6.2024-0683
[8] J. P. Slotnick, A. Khodadoust, J. Alonso, D. Darmofal, W. Gropp, E. Lurie, D. J. Mavriplis, CFD vision 2030 study: a path to revolutionary computational aerosciences, NASA Report Number: NASA/CR-2014-218178, 2014.
[9] J. J. Bertin, R. M. Cummings, Critical Hypersonic Aerothermodynamics Phenomena, Annual Review of fluid Mechanics, Vol. 38:129-157 (Volume publication date January 2006), https://doi.org/10.1146/annurev.fluid.38.050304.092041
[10] J. D. Anderson Jr., Fundamentals of Aerodynamics, Sixth Edition, McGraw Hill, 2017.
[11] C. E. Cockrell Jr., Aerosciences, Aero-Propulsion and Flight Mechanics Technology Development for NASA's Next Generation Launch Technology Program, AIAA Paper No. 2003-6948, AIAA International Space Planes and Hypersonic Systems and Technology Conference, Norfolk, VA, December 2003. https://arc.aiaa.org/doi/10.2514/6.2003-6948
[12] G. A. Tirsky, Up-to-date Gasdynamic Models of Hypersonic Aerodynamics and Heat Transfer with Real Gas Properties, Annu. Rev. Fluid Mech. 1993, 25, pp 151-181. https://doi.org/10.1146/annurev.fl.25.010193.001055
[13] H. K. Cheng, Perspectives on Hypersonic Viscous Flow Research, Annu. Rev. Fluid Mech. 1993, 25, pp 455-484. https://doi.org/10.1146/annurev.fl.25.010193.002323
[14] J. Urzay, The Physical Characteristics of Hypersonic Flows, Center for Turbulence Research, In ME356 Hypersonic Aerothermodynamics class notes. Center for Turbulence Research, Stanford University, 2020.
[15] C. Park, Assessment of Two-Temperature Kinetic Model for Ionizing Air, Journal of Thermophysics and Heat Transfer, Volume 3 Number 3, 1989. https://arc.aiaa.org/doi/10.2514/3.28771
[16] G. A. Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford University Press, 1994.
[17] ANSYS. Ansys Academic Research, release 2024, help system, Ansys Fluent Theory guide, Ansys, inc.
[18] H. G. Weller, G. Tabor, H. Jasak, C. Fureby, A tensorial approach to computational continuum mechanics using object-oriented techniques, Computers in Physics 12 (6), 1998. https://doi.org/10.1063/1.168744
[19] F. Piscaglia, F. Ghioldi, J. E. Guerrero Rivas, I. Spisso, A Unified Implicit Density-based GPU Coupled Solver for Hypersonic Flows Computations in OpenFOAM, AIAA SciTech Forum, 6-10 January 2025, Orlando, FL, USA.
[20] F. Ghioldi, F. Piscaglia, Acceleration of supersonic/hypersonic reactive CFD simulations via heterogeneous CPU-GPU supercomputing, Computers & Fluids, Volume 266, 2023. https://doi.org/10.1016/j.compfluid.2023.106041
[21] S. Oliani, E. Fadiga, I. Spisso, L. Capone, F. Piscaglia, GPU-accelerated Linear Algebra for Coupled Solvers in Industrial CFD Applications with OpenFOAM, arXiv preprint arXiv:2403.07882, 2024. https://arxiv.org/abs/2403.07882
[22] D. C. Wilcox. Turbulence Modeling for CFD. Third edition, DCW Industries, 2006.
[23] L. Huebner, A. Mitchell, E. Boudreaux, Experimental results on the feasibility of an aerospike for hypersonic missiles, 33rd Aerospace Sciences Meeting and Exhibit, 9-12 January 1995, Reno,NV,USA. https://doi.org/10.2514/6.1995-737

The Digital Engineering Method to Manage Complexity and Ensure Digital Continuity in Rotorcraft Development Processes

Luigi Turco, Luca Castaldi

Leonardo-Helicopters Division

Digital Engineering is an evolution of the Model-Based Systems Engineering methodology aimed at managing and taking advantage of digital models and artifacts to support engineering activities in the design, manufacturing, and maintenance stages of the product lifecycle. It focuses on establishing digital continuity across models and databases to enable cross-domain data traceability, easier flow of updates between depending elements, and prediction of impacts on project cost and schedule due to unforeseen design change requests. The method also encompasses the models integration and usage of in-service data to create counterparts of physical systems in the digital world, validate the design and predict the system behaviour in complex operating contexts. This paper briefly describes the digital engineering methodology and the approach to its adoption for rotorcraft design in Leonardo, as well as an example application for safety assessment of the helicopter design.

INTRODUCTION

Coping with Complexity of Leonardo products: Systems Engineering and MBSE

Leonardo products are characterized by high inherent and external complexity. It is inherent because of their degree of technology innovation, and often also due to the sheer amount of components that constitute the product. it is external, because many products need to cope with the high unpredictability of the mission they will perform, and also because the operational scenario encompasses many actors interfacing with it. Such a complexity at multiple levels is managed via the methods pertaining to the Systems Engineering discipline, which is defined as the 'Discipline that concentrates on the design and application of the whole as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect' [1].
In the last two decades, the spreading of digital models for detailed design activities has led to perform also he thigh-level, functional analyses and requirements management work that are typical to systems engineering with the support of digital models. This methodology is called Model-Based Systems Engineering (MBSE) and is defined as 'The formalized application of modelling to support systems engineering processes, i.e. requirements capture, design, analysis, verification, and validation activities, beginning in the conceptual design phase and continuing throughout development and later life cycle phases' [2].

From MBSE to Digital Engineering

The MBSE methodology takes advantage of any kind of digital model produced throughout the system development stage, as appropriate to support Integration, Verification, and Validation (IV&V) activities. Most of these models are not produced and maintained by systems engineers themselves, but by other engineering specialists. This has introduced new challenges, including:

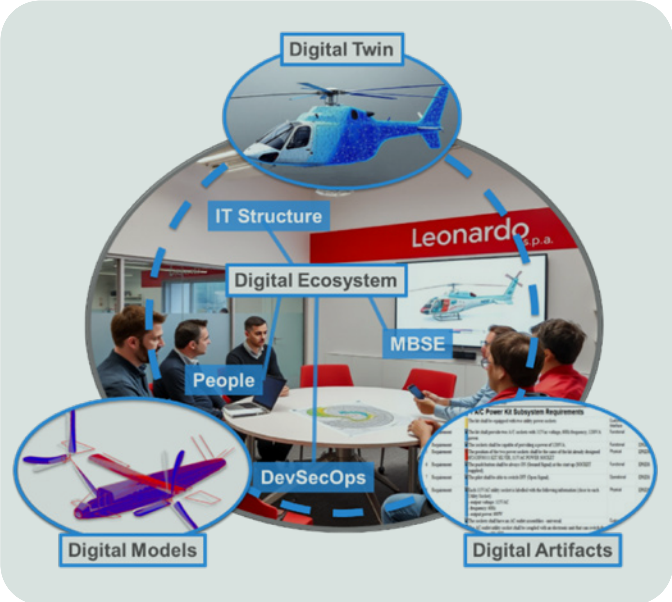
- having common policies and infrastructure to share models;
- control models versioning, in relationship to their physical counterparts, throughout the development stage;
- strengthen the links between models and requirements or other engineering artifacts;
- aggregate models of various engineering disciplines for IV&V purposes.

The model-based approach has also opened the possibility to exploit the value of models beyond the development stage, to support product assembly and service (e.g. for condition-based maintenance).
All the reasons above call for deeper integration of digital models and artifacts throughout the entire product lifecycle, thus establishing digital continuity in terms of data traceability, aggregation, and flow from one database, model, or artifact into another one in the digital world. This enlargement of scope has led the MBSE to evolve into Digital Engineering.

DIGITAL ENGINEERING AT A GLANCE

Definition of Digital Engineering

Despite the term Digital Engineering (DE) appears occasionally in software and electronics engineering literature since the 1960s, the modern interpretation of this term was introduced in 2018 by the United States (US) Department of Defense (DoD) Office of the Under Secretary of Defense for Research and Engineering in the Digital Engineering Strategy whitepaper [3]. It is formally defined in the DoD instruction 5000.97 [4] as 'a means of using and integrating digital models and the underlying data to support the development, test and evaluation, and sustainment of a system'. Usage of digital models and artefacts in certain engineering activities is a well-established practice in various disciplines and industries. However, these models were typically employed only to support analyses and the creation of engineering documentation. Conversely, DE considers the digital models as the main deliverable and source of truth for technical coordination, requirements specification, and item design definition.
The aforementioned DoD instruction also identifies the four main DE components: digital models, digital artifacts, digital threads, and digital ecosystem, as schematized in Figure 1.



1 – Digital Engineering Components

Digital Models and Digital Twins

Digital models encompass a broad range of possible representations of the system of interest, may it be an item, an onboard system, an aircraft, or the whole mission context. According to the International Council for Systems Engineering (INCOSE) guidelines [2], model types include the logical, quantitative, and geometric ones. Logical models capture the functional and logical relationships among the system elements and are often based on the network graphs theory.
Quantitative models use mathematical relationships to produce numerical results from simulations, e.g. vehicle dynamics simulators. Geometric models represent the system geometry, like Computer-Aided Design (CAD) models. Another key element of digital engineering is the Digital Twin, which is a special kind of digital model made of a purposefully integrated set of other digital models that represent the digital counterpart of the real system of interest (or a portion of it).

Digital Artifacts

Digital Artifacts are the instantaneous capture of certain aspects of the system digital models. They include quantitative data sets, model views, and textual documentation extracted from the digital models.

Digital Threads

According to the Digital Manufacturing and Design Innovation Institute (DMDII) [5], digital threads are electronic files and data pathways that enable the re-purposing, reuse and traceability of information in the development, definition, production and support of a part or of a system throughout its lifecycle.

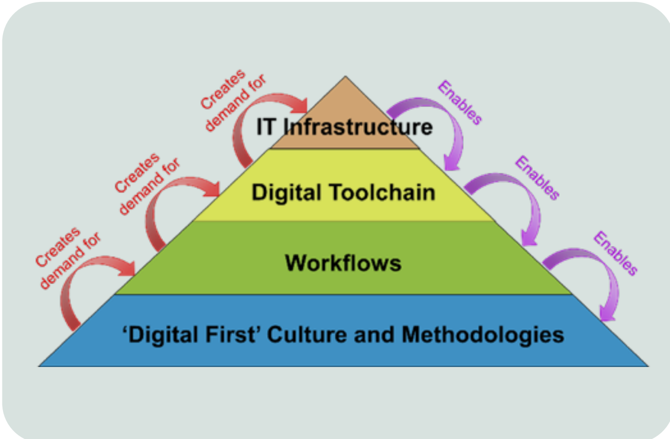
The Digital Threads Architecture (DTA) is the framework that connects models and artifacts in the digital worlds to track its evolution throughout the product life cycle and its integration with other elements. In the DTA, a central database is identified as the unique Authoritative Source of Truth (ASOT) for each kind of information and for all product lifecycle stages, as recommended by the US DoD Digital Engineering Strategy [3].

Digital Ecosystem

The digital engineering ecosystem is the set of hardware infrastructure, tools, DTA, skilful individuals, workflows, and engineering methodologies that participate in creation and usage of the DE outputs. The two most relevant methodologies for digital engineering adoption are the Model-Based Systems Engineering (MBSE) and the DevSecOps, i.e. the integration of security testing in the development and delivery processes.

KEY ENABLERS FOR TRANSITION TO DIGITAL ENGINEERING

Leonardo is embracing the digital engineering approach for rotorcraft design. In order to define and deploy the digital ecosystem, all key aspects are addressed: 'Digital First' culture and methodologies, workflows, digital toolchain, and Information Technology (IT) infrastructure. Each of these enablers supports the achievement of another one, as it is depicted in the pyramid diagram of Figure 2. It is in fact an inverted pyramid: the aspects below require those above them to be implemented. However, the aspects at the bottom of the pyramid are capable of generating a purposeful and effective demand to stimulate the innovation toward digital engineering adoption. Starting the ecosystem design from the pyramid base element ensures the transformation initiatives toward DE adoption are approached top-down, following the guidelines pushed by the upper management, but also bottom-up, as they are pulled by the workforce that has embraced the 'Digital First' culture. Each concept is briefly described in the following paragraphs.



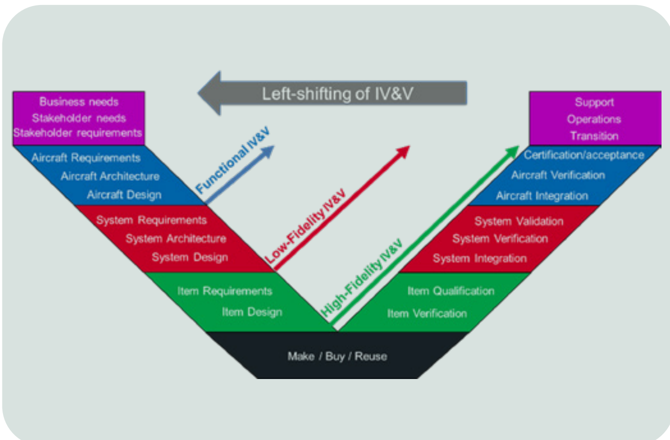
2 – Digital Ecosystem Enablers Pyramid

'Digital First' Culture and Methodologies

Spreading systems engineering and digital engineering culture and acquiring skills in these novel methodologies within the engineering community are key steps to generate the demand for digitalization that pulls the subsequent levels of the pyramid.

To be accepted and effectively adopted by the engineering community, DE requires a mind shift from focusing on creating tangible products to defining digital prototypes of the products and services required by customers and other stakeholders. These prototypes are the blueprints of the final products, and they are employed to anticipate Integration, Verification and Validation (IV&V) results before the actual product is manufactured or purchased. The anticipation of IV&V in the digital world is performed:

- at different levels of fidelity of the digital counterpart with respect to the physical item;
- iteratively, as the models are refined thanks to the data acquired throughout the product life cycle from testing, operational usage and maintenance activities on the physical counterparts.



3 – Anticipation of IV&V in the Vee Model

This concept is represented in Figure 3 via the IV&V arrows that detach from the left leg of the systems engineering Vee process model. This is why the approach is also called 'left-shifting'. In Leonardo, such an approach that is focused on left-shifting, exploitation of novel technologies for digitalization of engineering activities and creation of rapid feedback cycles between digital-based predictive models and real-world data, is referred to as the 'digital first' culture.
To foster the spreading of the 'digital first' mindset troughout the engineering community, learning paths made of multiple courses, workshops, certification exams in key disciplines are provided to the workforce. Key disciplines include, but being not limited to, systems engineering, with a focus on MBSE, and agile engineering management.

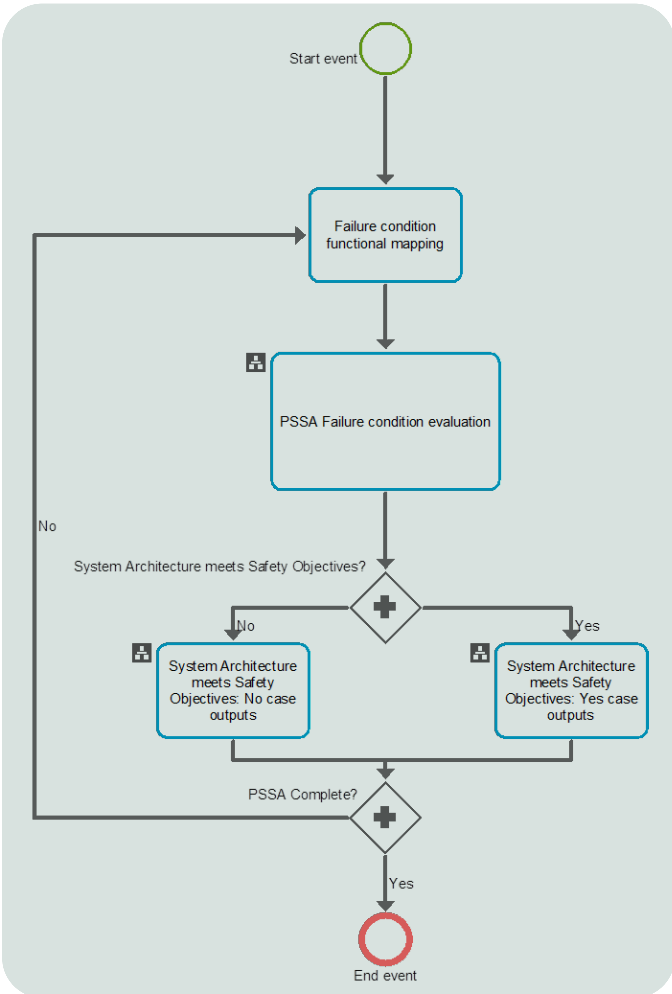
Workflows

Workflows are the ordered sets of tasks assigned to specific organization breakdown elements, which are necessary to achieve the desired objective starting from predefined inputs. In DE, defining workflows ensures that the digital threads are exploited and maintained appropriately by the users, and the selected methodologies are adopted to ensure effectiveness and to boost efficiency.
Workflows are designed and analysed for optimization via Business Process Models (BPM) diagrams based on formal, standardized graphical languages, like BPMN (Business Process Model and Notation, ref.[6]), as sampled in Figure 4. Due to large extension and complexity of the DTA, workflows are often enforced via workflow automation tools, that notify users when they are allowed or required to start their task, send and require specific information to share among tasks, etc.

Digital Toolchain

In a DTA, the toolchain is the integrated set of digital solutions that allow to perform DE typical activities such as modelling, simulation, configuration control of both models and digital items, sampled data analysis, and cross-tool data flow and tracing activities. Per each digital thread in the ecosystem and per each workflow related to such thread, there should exist a set of integrated tools that allows to perform each workflow step in the digital environment, and to trace and/or convey each step output data to the other ones, as suitable. Even though most tools depend on the particular discipline or product related to each digital thread, there are some key capabilities that characterize the digital engineering ecosystem:

- a Product Lifecycle Management (PLM) tool, to manage the configuration control of both digital and physical items. It also allows the sharing, review, and signature of digital artifacts. The PLM organizes the data in Bills Of Materials (BOM) in each lifecycle stage: Functional-BOM in the concept/early design stage, Design-BOM for the final design configuration, Manufacturing-BOM for production and assembly components, and service-BOM for in-service support items.
- A system functional modelling tool that describes from the functional and logical point of view the architecture of the product and its relationships with the foreseen operational environment. These architectural descriptions use formal graphical languages, the most popular being SysML [7].
- A Simulations Lifecycle Management (SLM) tool, that allows sharing, configuration control and integration of models and simulations.



4 – Example Workflow Diagram in BPMN Language

The SLM manages the digital models as much as the PLM manages digital artifacts. As more, the SLM allows models aggregation according to the logics captured in the functional and/or logical architecture to create Digital Twins of the product.
- A tool to manage the large amount of data acquired during testing, operations, and service activities.
- A DTA management tool that ensures digital continuity by tracing digital model elements and data across databases. It should also allow to push changes introduced in one artifact or model toward all other model elements and data that depend on it. This tool can be a set of applications that fulfil the role for different digital threads, or an overarching platform that interfaces with most of the toolchain, or a functionality of the PLM tool.

PLM and SLM represent, each for their own scope, the single ASOT that allows to inspect and refine digital models and data throughout the lifecycle.
The above list is complemented by the domain-specific tools employed for design and development.

IT Infrastructure

The IT infrastructure is the foundation that hosts the digital environment, i.e. both tools and information. It includes databases for models repository, links to collect data from the physical instances of the product and its components, and computing resources, including high-performance ones for real-time and/or high-fidelity simulations of digital models. An IT infrastructure for digital engineering should feature the following characteristics:
- grant access to external stakeholder, e.g. contracting and certification authorities, so that they can participate in early validation activities based on the digital models;
- connect databases of different disciplines and organizational units, to grant digital continuity across the development phases and involved actors;
- provide a means to acquire and store data from testing, usage, and maintenance of physical instances of the digital models;
- ensure cyber resilience for the aforementioned pathways.

Deployment Approach

The digital ecosystem is an overarching entity, whose deployment affects a large engineering community and most of aircraft components development processes. In order to cope with such complexity, the transition is approached by creating a discipline-focused or aircraft subsystem-focused digital thread at a time. Each digital thread analysis aims at introducing the four digital ecosystem enablers in order to increase efficiency of the engineering of an aircraft component (e.g. airborne software, drive system, wiring and harness, etc.) or to meet the goals of a certain discipline (e.g. assessing the safety of the design, performing the cybersecurity analysis, etc.). This approach allows to build and deploy the digital ecosystem, incrementally.

A DIGITAL THREAD DEFINITION EXAMPLE: DIGITAL CONTINUITY FOR ROTORCRAFT DESIGN SAFETY ASSESSMENT

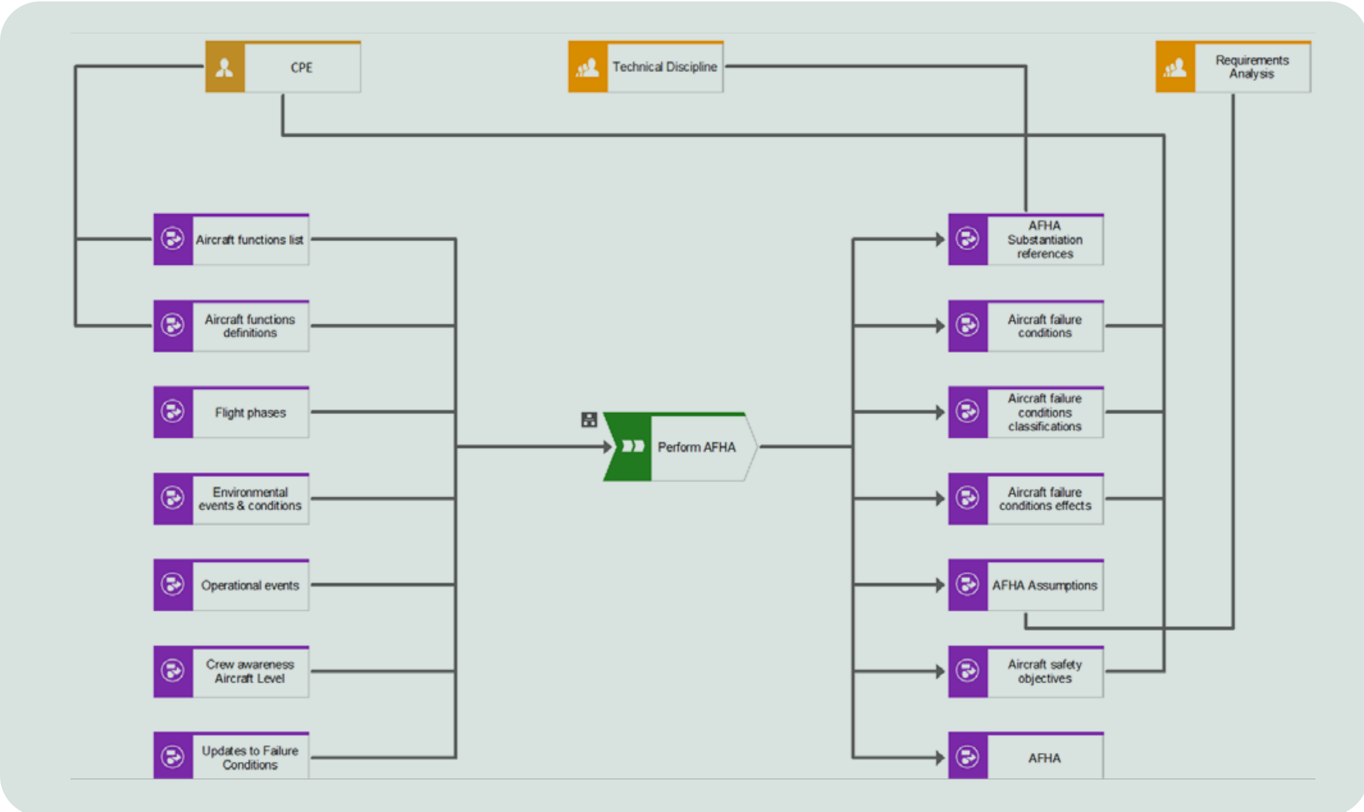
The transition toward digital engineering is ongoing in Leonardo, with various digital threads defined. The digital thread to support the safety assessment of rotorcraft platform and onboard systems design is described here after, as an example application of the concepts introduced here above.

Model-Based Safety Assessment Methodology

The objective was to go shifting from a text document-based assessment, towards the Model-Based Safety Assessment (MBSA) methodology, as described by [8], ensuring adherence to the applicable regulations and recommended practices for safety in aeronautics.
To support the transition, the domain experts that worked at the thread definition were provided with training sessions on the MBSE and agile methodologies.

Workflow

The to-be safety assessment process was defined in adherence to the Aerospace Recommended Practice (ARP) 4761A [9], which is an acceptable means to show compliance to airworthiness certification requirements (ref. [10]).
Starting from the reference ARP, a process model tailored on Leonardo organization was designed. An example of the BPM functions allocation diagram is shown in Figure 5.

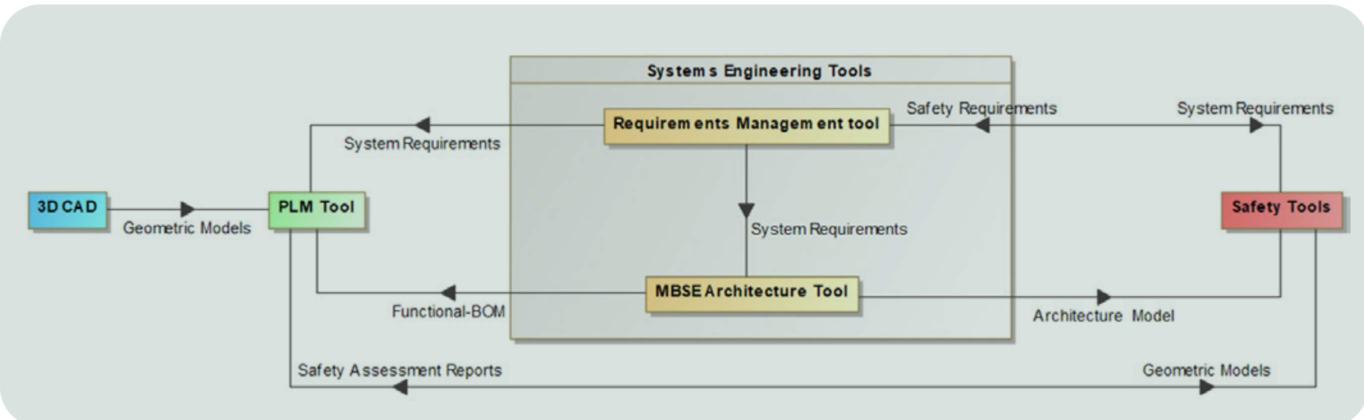


5–Functional Allocation Diagram for Aircraft Functional Hazard Assessment

Validation of Toolchain and Infrastructure Proposals for the Safety Assessment

Each step identified in the workflow was matched to the tools already adopted in Leonardo to identify gaps and areas of improvement. Then, a research of off-the-shelf alternatives available in the digital solutions market was carried out, for those steps that were missing a tool based on digital models and databases. Roughly 20 tools were identified to complete the toolchain. A benchmarking of each tool was carried out against the requirements provided by the safety process stakeholders, including needs of digital continuity across tools. The tools interconnections are illustrated by the map in Figure 6.

In order to validate the proposed digital thread, the tools and supporting IT infrastructure were acquired and employed to carry out the complete safety assessment workflow on a small but representative example.



6–Safety Digital Thread Schematic

CONCLUSIONS

Digital Engineering (DE) is an evolution of the Model-Based Systems Engineering, overarching all the product lifecycle stages and most of engineering disciplines. The method is based on four pillars: digital models, digital artifacts, digital threads, and digital ecosystem. The method promises to guarantee digital continuity across the works of different organizational units and digital artifacts, to boost communication, information reusability, and design validation, as well as supporting assembly and maintenance activities. Leonardo is building the DE ecosystem incrementally, for one discipline or system at a time, via the following four steps: spreading of 'digital first' culture with dedicated training, definition of the to-be workflow based on novel methodologies, definition of an integrated toolchain, and setup of the supporting IT infrastructure. An example case is the digital thread supporting the safety assessment of rotorcraft design. Even though the transition is ongoing, the large amount of areas and tasks that are impacted will prolong this transformation for many years. Key elements to support and accelerate the transition are the cultural shift to embrace digital model-based approaches, the centralization of IT infrastructure and services management to establish single authoritative sources of truth and enable economies of scope, and the introduction of new roles dedicated to DE-specific activities in the company.

Luigi Turco: luigi.turco@leonardo.com

REFERENCES

[1] Systems Engineering Manual, Federal Aviation Administration (FAA), ver. 3.1, 2006.
[2] D.D. Walden, T.M. Shortell, G.J. Roedler, B.A. Delicado, O. Mornas, Y. Yew-Seng, D. Endler, INCOSE Systems Engineering Handbook, 5th ed., Ed. Wiley, 2023
[3] Office of the Deputy Assistant Secretary of Defense for Systems Engineering, "Digital Engineering Strategy", United States Department of Defense, Washington, D.C., 2018.
[4] Office of the Under Secretary of Defense for Research and Engineering, DoD Instruction 5000.97 "Digital Engineering", United States Department of Defense, Washington, D.C., 2023.
[5] https://www.mxdusa.org
[6] Business Process Model and Notation (BPMN) specification, Object Management Group (OMG), v2.0.2, 2013
[7] Systems Modeling Language (SysML) specification, Object Management Group (OMG), v1.6, 2019
[8] M. Sun, S. Gautham, Q. Ge, C. Elks, C. Fleming, "Defining and characterizing model-based safety assessment: A review", Safety Science, vol. 172, Apr. 2024.
[9] Aerospace Recommended Practice (ARP) 4761, Society of Automotive Engineers (SAE), rev. A, 2023
[10] Advisory Circular (AC) 29-2C "Certification of Transport Category Aircraft", Federal Aviation Administration (FAA), 2014

Driving Innovation with Digital Continuity and Product Lifecycle Management in Leonardo

Francesco Di Cintio[1], Viviana La Marca[2], Gianmarco Rapisardo[1], Martino Giobbio[1], Alessandro Baratelli[1], Andrea Campanile[1], Andrea Vergani[1], Riccardo Bianchi[1], Simone Maugeri[1]

[1]Leonardo – Helicopters Division, [2]Leonardo - Corporate/Strategy and Innovation

In the ever-evolving landscape of aerospace and defence, Leonardo is at the forefront of digital transformation, by leveraging Digital Continuity and Product Lifecycle Management (PLM) to enhance competitiveness and efficiency. As the industry shifts towards more integrated and simultaneous processes, the need for real-time, reliable data across all stages of the product lifecycle becomes paramount. This transformation is not just about adopting new technologies but about rethinking how we manage and utilize data to drive innovation and maintain a competitive edge.

INTRODUCTION

In today's fast-paced industrial and manufacturing landscapes, effective data management across product lifecycles is essential for efficiency and innovation.
Key concepts such as *Digital continuity, Digital thread,* and *Product Lifecycle Management* (PLM) play central roles in this ecosystem.
For the sake of clearness and completeness, in this work we assume the following definitions:

- the **Digital continuity** refers to the seamless integration and flow of data across different stages and systems, ensuring that critical information remains accessible and consistent throughout a product's lifecycle;
- the **Digital thread** is a strategic approach to connect the product information, to understand why something has happened;
- the **PLM** is a framework that implements the Company's digital thread connecting product data across various stages, from design and development to manufacturing and maintenance, to provide a single, unified view of a product's history and real-time status.

According to a more holistic view, the PLM is "the source of truth" for all product data, and it is the communication system between all product stakeholders: principally engineering, manufacturing, configuration management, program management and customer service, as well.

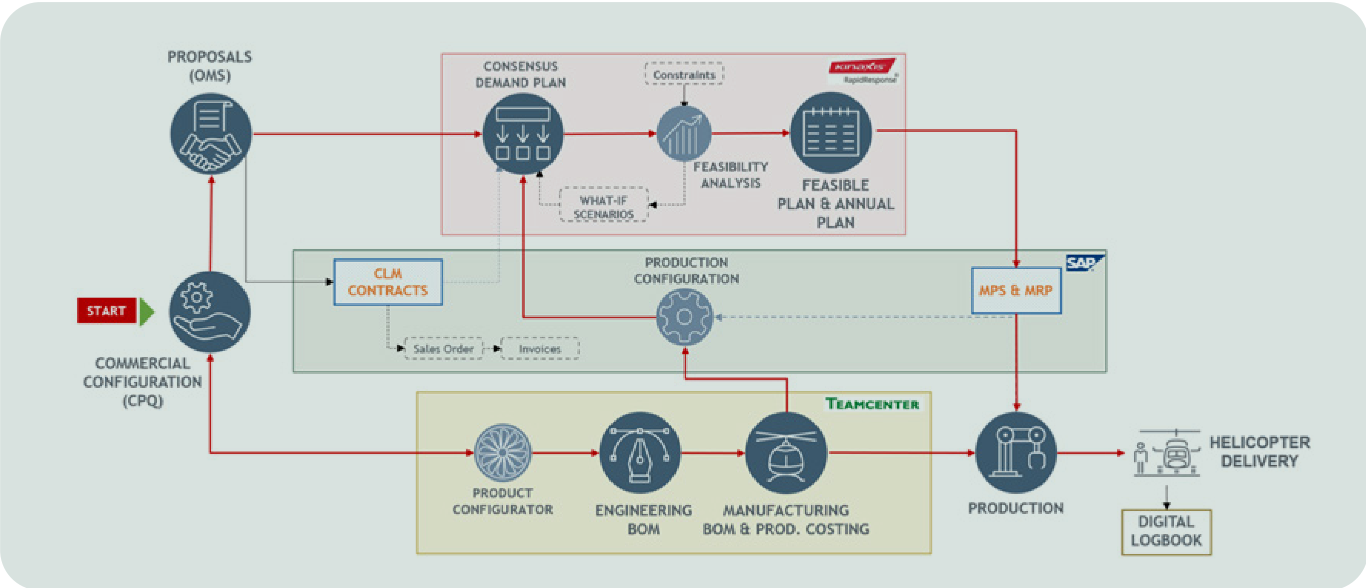
THE EVOLUTION OF PRODUCT LIFECYLE MANAGEMENT

The traditional approach to Product Lifecycle Management (PLM) at Leonardo Helicopters Division has long been a cornerstone in managing the lifecycle of our products, from initial design to final disposal.
However, as our products have become more complex, the limitations of traditional Product Data Management (PDM) systems have become more apparent. They often focus on managing the Computer Aided Design (CAD) structure and the associated engineering bill of materials (EBOM), that is a detailed list of components, assemblies, and materials required to design and build a product, as defined by the engineering team. Since this approach was effective in their time, today it loses sight of critical aspects such as, on the one hand, the integration of the requirements and functional design before the development phase is started and, on the other hand, integrating the change and the configuration management process within a single environment when the production is initiated.
By integrating the digital thread tools, Leonardo can gain advantage from the following core functionalities provided by such a tool, which include:

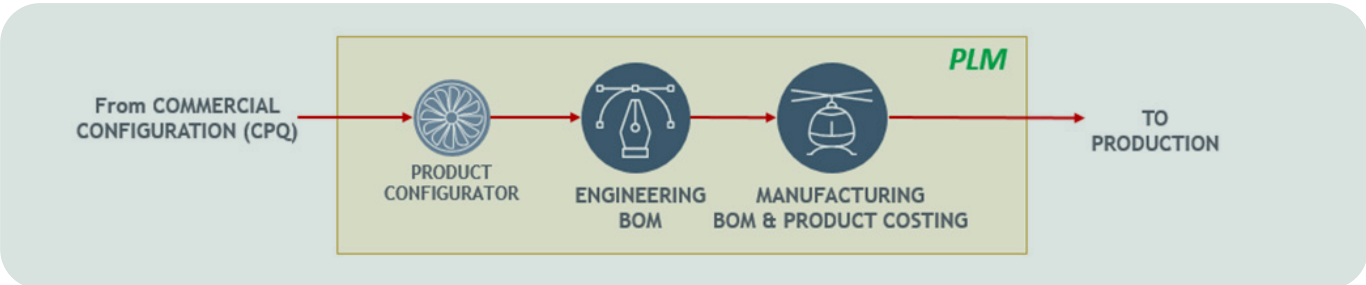
- sesign and drawings release process management, including relevant documents;
- workflow and process management for approving changes;

- product structure (bill of material, BOM) handling at engineering, manufacturing and production level;
- product data centralization;
- materials content identification for environmental compliance;
- company's ERP systems (i.e. SAP) interface.

Adapting the PLM to support digital continuity involves leveraging advanced technologies and methodologies such as the Model-Based Systems Engineering (MBSE). This allows us to gather and assess requirements more effectively, develop feasible concepts, and ensure that all aspects of the product lifecycle are interconnected. The benefits and outcomes of this evolved PLM system are significant: by ensuring that data is available and reliable in real-time for all stakeholders, we can streamline operations, reduce errors, and make more informed decisions. This not only enhances our competitiveness but also aligns with our commitment to **sustainability** by reducing the time, energy, and resources required for product development. As we continue to innovate and expand our product range, the evolved PLM system will be instrumental in maintaining our position as a leader in the aerospace industry.
Step-by-step, the process along an integrated digital architecture includes operations "to" and "from" the PLM, through its connection with the other relevant part of the architecture, as depicted in Figure 1. Since more tools contribute to implementation of the Company's digital continuity, in the following of this work the focus is on the management of the product data within the PLM (Figure 2).



1–Digital continuity functional architecture



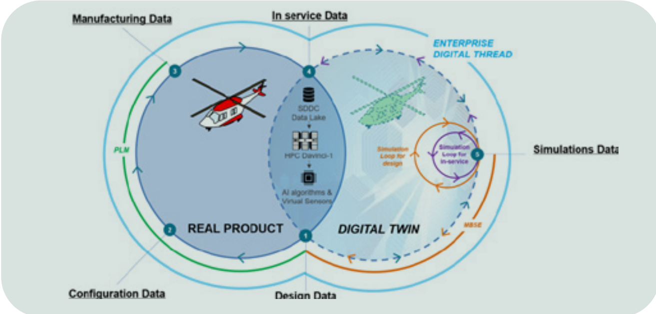
2-Focus on PLM macro-functionalities

THE DIGITAL CONTINUITY IMPLEMENTATION STEP-BY-STEP

Starting from the commercial configuration of an existing product (**step 1**) or from the conceptual design of a new one, the final desired product configuration is controlled through an embedded configuration control process to produce the detailed list of the relevant "technical items", the bid of materials. The Manufacturing can then use the design information to create a detailed manufacturing path, which can be passed to downstream

systems such as the Enterprise Resource Planning (ERP) and the Manufacturing Execution System (MES) to generate work instructions, allocate resources and supervise operations (**step 2**).
The integrated product costing allows calculating the costs for new products and their quotations early in the product lifecycle. It also allows quickly identifying cost drivers and easily simulating and comparing alternatives, as well as predicting future product costs and prices by using the profitability calculation to secure product investments (**step 3**).
The PLM systems can also be integrated with simulation tools that allow our Company to optimize the design process, for example to enhance the prototyping and ergonomics simulation. Moreover, by integrating the Rotorcraft Digital Twin (see Figure 3), the PLM is streamlining operations and enhancing the interaction with external stakeholders, such as suppliers and customers, since the conceptual design phase of the product. This integration is crucial as it allows for better decision-making and process optimization, ultimately leading to a more cohesive and responsive industrial environment.

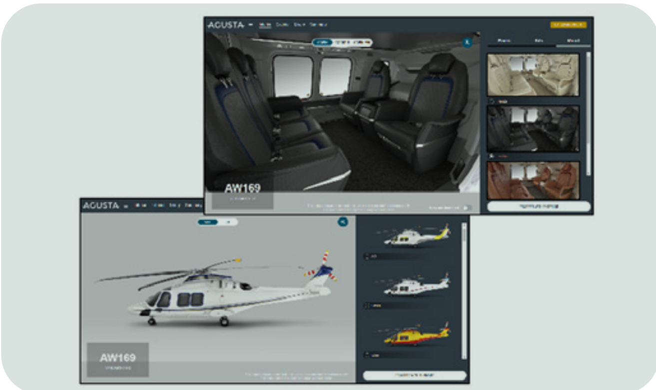
The role of the PLM in this digital transformation cannot be overstated: it is essential for managing the entire lifecycle of a product, ensuring that all technical data and project changes are efficiently stored and handled.
As Leonardo continues to expand its product range and integrate more complex technologies, the need for a robust digital framework becomes even more critical. The transition to a digital ecosystem is not just a technological shift but also an organizational one, which requires a unified approach to engineering and data management.



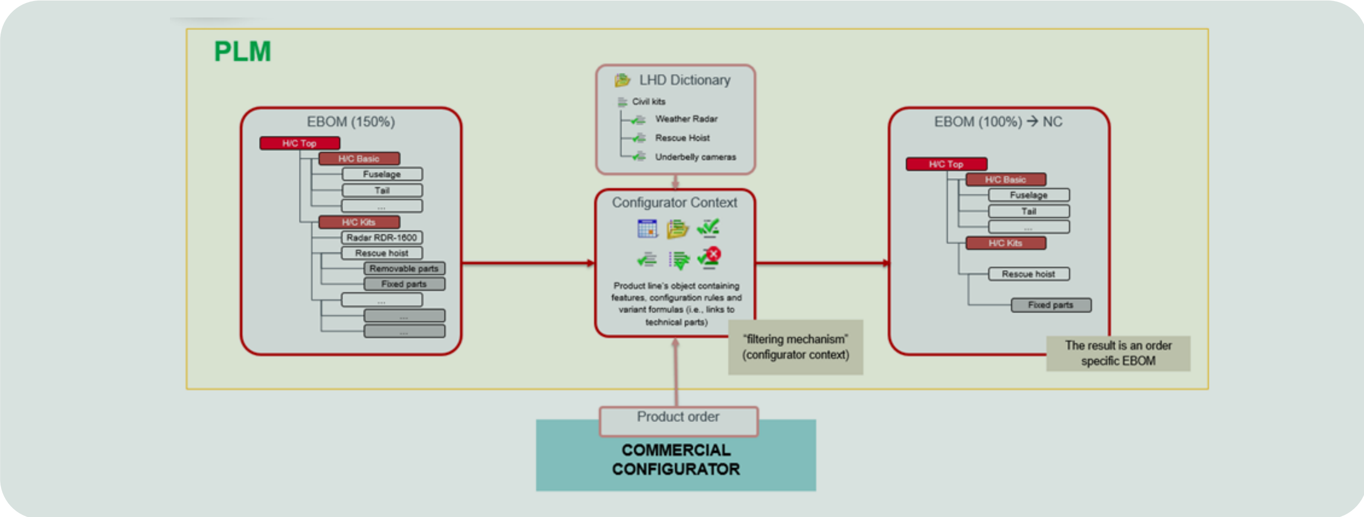
3 – Enterprise digital thread connects the real product to the Rotorcraft Digital Twin

Step 1 - Configuration Management within the PLM

The journey begins with the Commercial Configuration: the Leonardo sales managers engage customers with a dynamic digital catalogue that enables customizing helicopters configurations according to their needs and requirements. Once the commercial configuration is created, according to the high-level compatibility rules embedded in the configurator, it is transferred to the product configuration control system integrated into the PLM. This allows defining product options (i.e., objects that can be selected or not), variants (i.e., objects that can be used as alternative to others) and versions based on specific rules and technical constraints, ensuring that only feasible and compliant configurations are created, while customer requirements are fully captured.
Applying specific configuration rules, the system is capable to manage both the 100% configured structure and the 150% structure, in order to perform a trade-off study. The 150% structure includes every possible configurations of the product structure, while the 100% structure represents the configuration specific to a particular customer. The latter is obtained by starting from the 150% structure and by defining a specific setup according to customer requirements. This integration streamlines the configuration process through the design, by defining the corresponding EBOM and feeding the subsequent production phase (Figure 5) starting from the Development to In-Service phase.
The Configuration Management approach is not limited to technical purposes, but it guarantees, inside the PLM framework, the collection and the recording of impacts in terms of manufacturing, procurement, logistics, costs and performances.
This is crucial to assess costs and benefits and to determine which effects of the changes on planning, thus supporting the Program Management to take effective and strategic decisions on evolution of the configurations.
The adoption of the PLM ensures a unique repository for technical and functional records from the Bid phase to the In-service phase within the same environment, which improves traceability of the configurations.
Moreover, it enables real-time updates and collaboration between design and manufacturing, improving efficiency, reducing errors, accelerating the time to market and setting standard operating procedures for Configuration Control of the product lines at division level.



4 - Example of LHD Commercial Configurator with graphical interface (Demonstrator)



5–PLM Configuration process flow

Step 2 - From the Engineering BOM (EBOM) to the Manufacturing BOM (MBOM)

During the design phase, the PLM system interfaces the CAD to handle 3D drawings as well as detailed properties of assemblies and components as for the Engineering BOM (Figure 6). The design is controlled through revisions, to allow continuous updates and improvements, according to a well-defined and rigorous change process.

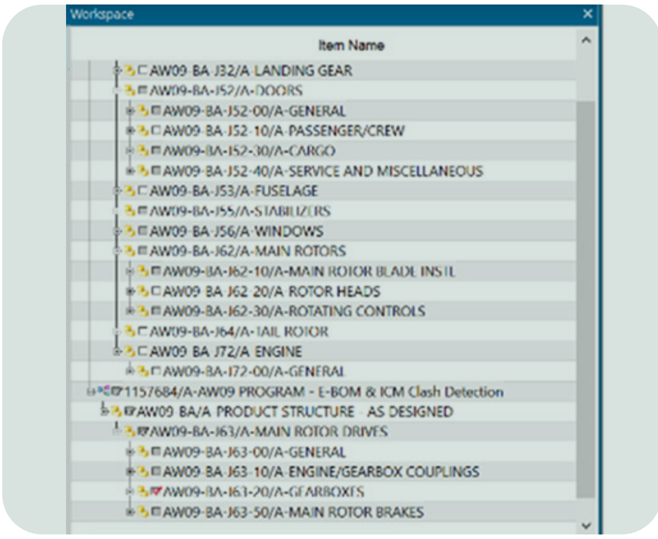
After the allocation of Baselines and through the application of Change management criteria defined within the PLM tool, the Configuration Management ensures:

- the correct identification of configurations;
- the subsequent control of the changes;
- the record of the change implementation status of the physical and functional characteristics.

As the design is finalized, the Manufacturing Bill of Materials (MBOM) takes over and guides the production line to ensure that every component is assembled to the exact specifications.
The PLM System ensures the continuous alignment between the EBOM and the MBOM, and guarantees that every engineering modification is simultaneously translated into a consistent production modification.
Dynamic indication of the EBOM parts assignment of the MBOM ensures that all the latest design changes are incorporated.
The system indicates which production process is impacted by the change. Then the user can easily see the product changed in the 3D viewer. The system allows the bidirectional transfer of product and manufacturing planning information between PLM and the ERP.

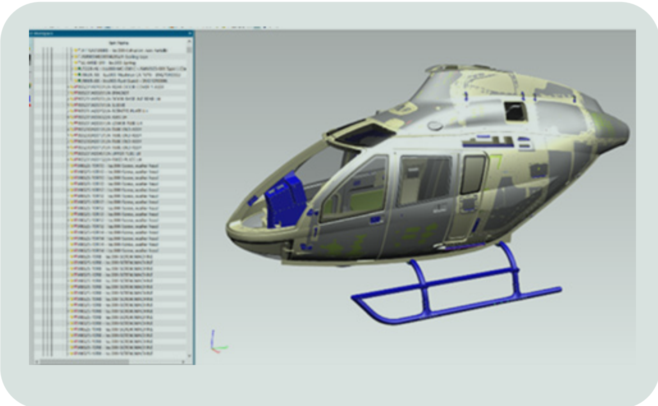
Step 3 - Product Costing Management

Since the PLM includes the EBOM, the MBOM and the configuration, it becomes possible to calculate the cost of any possible helicopter. The PCM, being it part of the PLM, enables continuous monitoring of helicopters costs at any phase of their products lifecycle, which helps the team in any decision making process. In a common platform it is capable of: supporting the definition of a cost effective configuration, comparing alternatives, combining BOM components with different maturity levels, collecting data from various sources and sharing results within the team.



6-Example of an Engineering BOM

BENEFITS OF MANAGING THE ENGINEERING PRODUCT STRUCTURE INSIDE PLM



7-Example of Digital Mock-up (DMU)

The first benefit is the representation of the digital mock-up (DMU) of the product, which allows typical DMU activities like interference, sectioning, measurement, 3D model comparison, clash analysis, and enables viewing it highlighted inside the structure representation, as it is depicted in Figure 7.
Other benefits are related to the capability to manage the change management process and the entire engineering product structure, no matter if the parts belong to a CAD model. By selecting a specific component, it is possible to navigate every information related to this component, for example in terms of change request, revision, requirements, or any model-based system representation we have defined in terms of Model Based System Engineering (MBSE) activities.

Acronyms

BOM Bill of Materials
CAD Computer Aided Design
DMU Digital Mock-up
EBOM Engineering BOM
ERP Enterprise Resource Planning
MBOM Manufacturing BOM
MBSE Model Based system Engineering
MES Manufacturing Execution System
PCM Product Costing Management
PLM Product Lifecycle Management
PDM Product Data/Design Management

CONCLUSIONS

The main challenges in introducing a PLM system go beyond the technical aspects and involve both the integration of new processes and the management of user adoption. With a broad impact across our Company's functions and geographies, the project requires a strategic, collaborative approach from the outset, which involves coordination between multiple departments and the central Digital Solutions team, to ensure robust competence foundation.

This collaboration is both cross functional and cross-geography as the first users come from different locations and sets an example of how the solution can "break down" internal silos. By bridging geographical and departmental boundaries, the project fosters a unified team aimed at a common goal. Such a strong, integrated collaboration is the clear, tangible benefit of the project, which underscores the power of the teamwork even before the full range of the anticipated outcomes is realized.

Francesco Di Cintio: francesco.dicintio@leonardocompany.com

REFERENCES

[1] M. Grieves, "Product Lifecycle Management", Michigan State University, Apr. 2006.
[2] D. Gerhard, S. Salas Cordero, M. Rossi et others, "MBSE-PLM Integration: Initiatives and Future Outlook", Product Lifecycle Management Enabling Smart X. 7th IFIP WG 5.1 International Conference, PLM 2020, Rapperswil, Switzerland, July 5–8, 2020.
[3] E. Subrahmanian, S. Rachuri and others, "The Role of Standards in Product Lifecycle Management Support", U.S. National Institute of Standards and Technologies, Jan. 2006.
[4] SIEMENS website. [Online]. Available: https://plm.sw.siemens.com/en-US/

NEMESI - Digital Twin for Production Processes & Training of Plant Operators

Alberto Di Donato, Vincenzo Pellegrino, Davide Santoro

Leonardo – Aerostructures Division

The Project NEMESI (New Engineering and Manufacturing Enhanced System Innovation) is a Research, Development and Innovation (RDI) project exploring innovative solutions for the life-cycle of airworthy primary structures. It is conceived in accordance with the transition to the digitalized factory of the complex primary aerostructures, such as the ATR Fuselage designed at the beginning of years '80 of the past century, within the industry 4.0 framework. As such, innovations concern the digitalized integration of the non-recurring and recurring phases of production of complex aerostructures in Campania Region, the proper and safe functioning of plant digitalized production activities. The RDI activities also include the studies aimed at the development of the concerned collaborative human-to-machine, and/or machine-to-human, and/or machine-to-machine workspace environments of the digitalized factory, also ensuring safety and growth of human competence/skill. A comprehensive detailed public description of the project has been notified and is reported in [1][2].

INTRODUCTION

In the framework of the digitalized plant of the industry 4.0, NEMESI RDI Project deals with the planned research and the critical investigation aimed at the acquisition of new knowledge and skills for bringing about a significant improvement in existing products, processes or services related to the "legacy 2D" complex aerostructures.
Referring to the fuselage of the ATR regional transport aircraft, it foresees applied research activities aimed at creating novel competences and capabilities to be exploited in novel processes and services such as in design, manufacturing and maintenance of complex aerostructures. It also refers to major improvements of the existing product based on regional aircraft, but it is also in view of new products based on narrow-body aircraft with further attributes suitable to be transferrable and/or reproducible to contiguous sectors.
As such and according to the Frascati Manual [3], the NEMESI RDI Project:

- explores "feedback R&D" because, even if the legacy 2D complex aerostructures has been turned over in production since the years '80 of the past century, most of the technical problems related to the product conformity demand further applied research in exploring exploring the potentials and the validations of the key enabling technologies and of their integration;
- aims at improving significantly the production of aeronautical parts and assembly, by developing new methods and/or standards and/or quality control procedures to support the first-time trials to test for tooling up to the new key enabling technologies;
- implies SW developments/integration of IT Architectures that are aimed at solving systematically the scientific and technological uncertainty of validating the Key Enabling Technologies and at increasing the related stock of knowledge for the
  - proper and safe functioning of plant digitalized production activities and of the concerned collaborative human-to-machine and/or machine-to-human and/or machine-to-machine workspace environments;
  - life-cycle of airworthy primary structures;
  - human competence/skill growth and safety;

The Project supports the digital transformation of the production processes for the non-recurring and recurring phases of complex aerostructures in Campania Region through:

- *Digitalization of the Product* – the development of the Model Based Definition (MBD) of the pilot case, based on the fuselage of the ATR aircraft, allows saving in assembly operations and facilitate maintenance processes;
- *Automation* – the automated assembly allows reduction and optimization of production cycle-time and inefficiencies, improving at the same time the product quality and the production flexibility;
- *Digitalization of Production Processes by integrating the Smart Factory technologies* – this allows to manage the production line in real time and to predict plant malfunctioning situations;
- *Development and testing of new training methodologies* – the field trial is based on the Key Enabling Technologies for the creation of new skills and competences of plant operators.

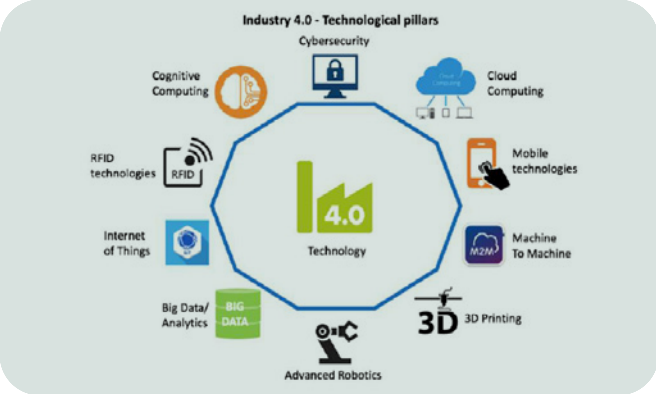
1– RDI NEMESI, Logo of the Partnership [4]

In the NEMESI RDI project Leonardo is the proposing partner and the 13 remaining Partners are the adhering ones. Figure 1 shows the logo of the Partnership related to the 14 Partners taking part into the research project.
A comprehensive detailed public description of the project has been notified and is reported in [1].

DIGITALIZATION OF PRODUCTION PROCESSES & SMART FACTORY

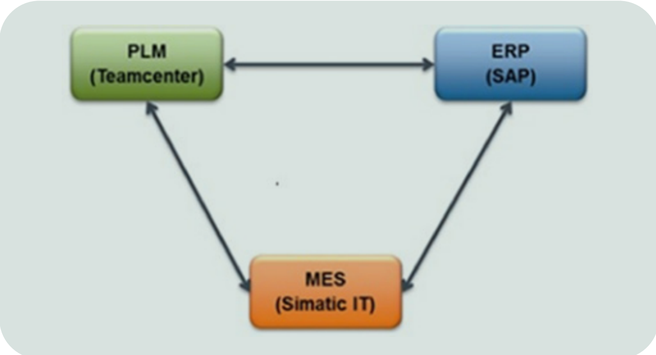
The RDI NEMESI project was born with the fundamental objective of exploring the Key Enabling Technologies for their future implementation in the peculiar industrial sector of the complex aerostructures. This is needed to respond to the modern concept of "Smart Factory", in which manual and automated processes are digitally interconnected with each other, to create the collaborative and sustainable environment that is essential for achieving high levels of efficiency and effectiveness. On this basis, the research project has been oriented on the following industrial processes, in order to experiment with the above digital technologies:

- advanced planning and scheduling;
- production execution;
- quality management;
- production and performance intelligence.

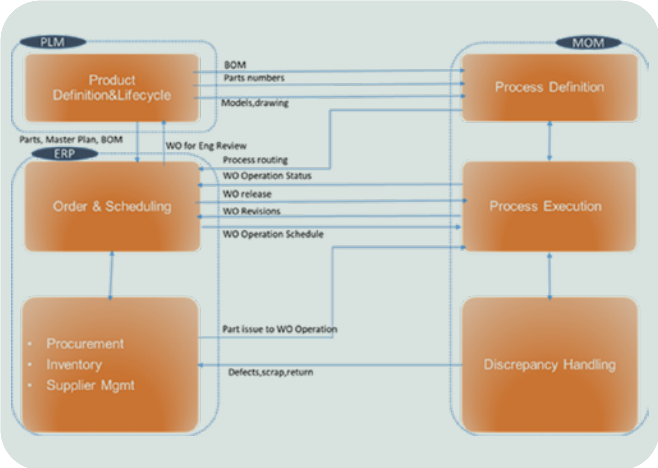


2–Industry 4.0, Technological pillars [5]

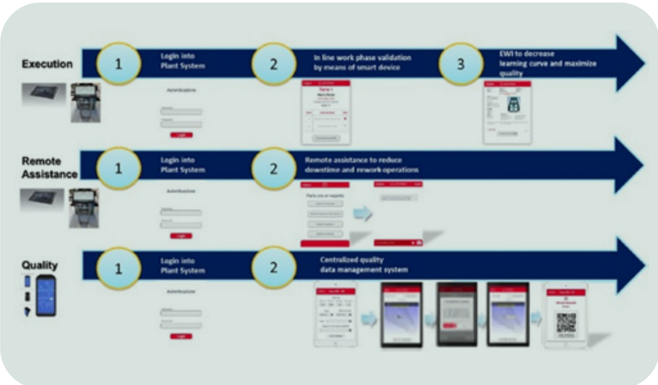
In detail, the sequence of activities includes the conception/design/realization of an environment/ architecture of SW and HW prototypes for the experimentation/simulation of daily production planning and related re-planning based on priority, progress and actual availability of tools, human resources and components. These prototypes receive digital data in real time from the systems placed along the production line (e.g., input stations, equipment status, work in progress on each workstation, etc.) involved on both manual and automated activities.



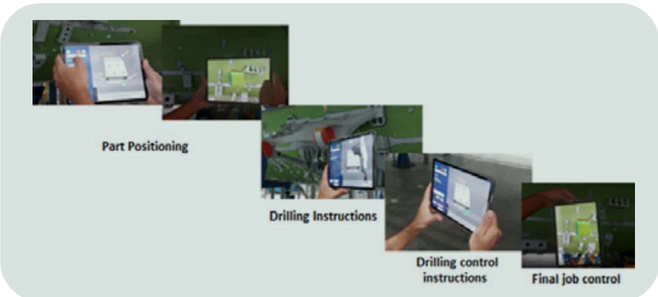
3–Closed Loop manufacturing scheme [6]



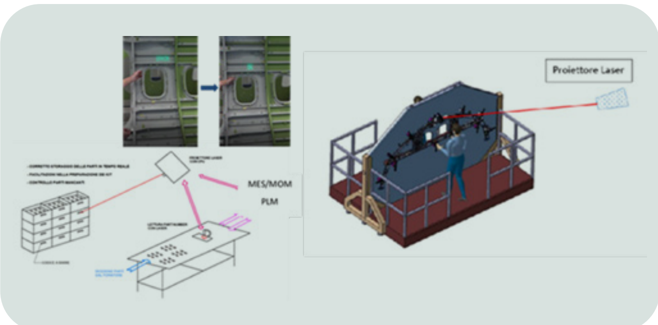
4–CLM Integration Flow [6]



5–Smart UI on mobile devices for plant operations [7]



6–Smart UI with AR/MR technologies [8]



7–laser/optics system for correct assembly support [9]

The related digitalized management in an integrated environment allows to streamline production flows, monitoring at the mean time the performances through specific digital dashboards (business intelligence) built on data analytics and artificial intelligence algorithms.
Once the data are collected and processed in real time, they can be easily fed back and shared at the basic automation level, thus triggering a virtuous circle that impacts the entire value chain and allows for improving all processes throughout the company.
In Leonardo IT systematic experimentation, the heart of this architecture consists of the innovative functional model that digitally integrates the Digital Product Life-Cycle Management/DPLM (selected the Siemens TCenter), the Manufacturing Execution System-Manufacturing Operations Management/MES-MOM (selected the Siemens OPCenter) and the Enterprise Resource Planning/ERP (selected the SAP). This represents the starting point for the implementation of digital processes within a modern industry.
Such model is known as 'Closed Loop Manufacturing' (CLM), and its logical integration structure is shown in Figure 3.

The mutual interactions of the three systems are described in the diagram in Figure 4.

This integration, will enable the data alignment between TCenter and MES for the operations of:

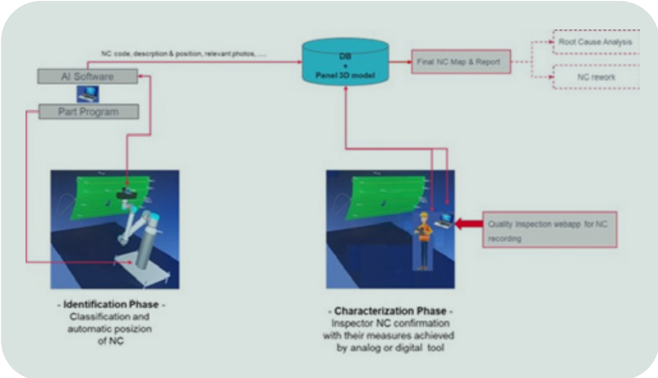
- cycle revisions for insertion\modification\deletion of work phase,
- association of a new Electronic Work Instruction (EWI) to a work phase,
- modification of an existing EWI,
- modification of work plan for a workstation.

To evaluate the benefits provided by the innovative system architecture in a digitalized plant, the following technological devices have been considered and tested on shop floor individually:

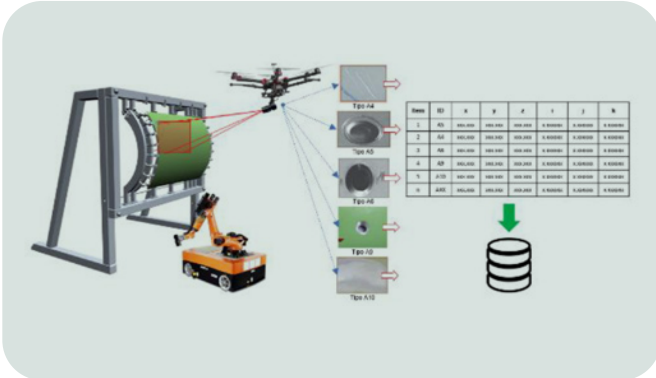
- IoT sensors distributed along the production line, to provide the status of the various automated operations in real time.
- Smart mobile devices (i.e., tablets, printer) to provide, via Smart UI, for both manual installation and quality control instructions in production and information on the status and times of operations towards the MES system, as it is sampled in Figure 5.

Benefits from such a systems architecture of digital technologies can be provided also by augmented/mixed reality technologies (Figure 6).

Benefits can come also from a laser/optics system for correct positioning of parts (Figure 7).



8 – Mercator's projection representation



9 – Characterization by autonomous laser optic device [11]

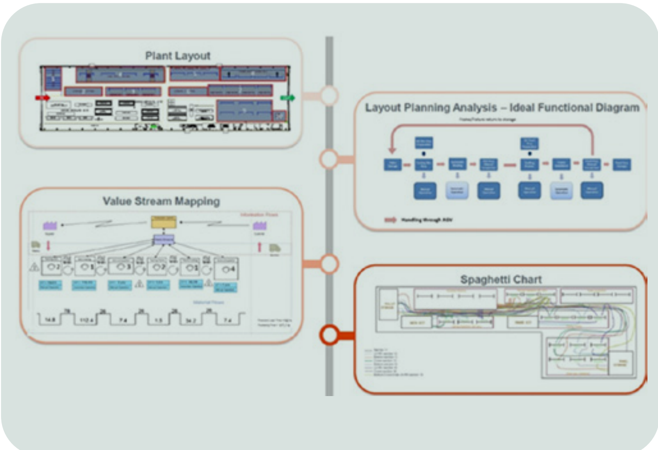
Robotic digital system (automatic/autonomous) for quality control can be integrated as well, based on analytical visual recognition/classification techniques by Machine Learning of non-conformities (NC) that combines artificial intelligence and machine learning technologies with manual characterization (measuring) of NC (Figure 8) and by characterization by robotic and laser technology (Figure 9).

Systems with RFID, BLE, Wi-Fi, UWB or GPS sensors technologies for continuous tracking: of assembly kits (from the warehouse to the various stations of the line) and of parts/components and assemblies along the production line.

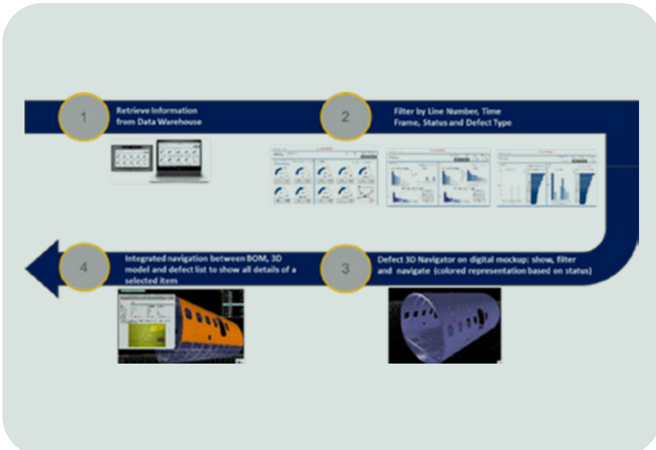
Simulation software, continuously aligned with the 'shop floor' processes by the above plant systems, to create what is called a '**Digital Twin**' of factory, with analytical capabilities to predict any problem in advance or to optimize process when occurs.
The data collected will be made visible at different company levels in terms of dashboard of quality KPI, and of ANDON on displays close to the workstations, showing in real time the operations KPI and their status with the purpose of raising the awareness of the "blue collars" (Figure 11 and Figure 12).

Almost the entire research project partnership contributes to this experimentation according to the scheme in Figure 13.

At the current time, not all the activities above have been completed. In particular, they will be necessarily integrated with the CLM architecture described above, according to the logic of a modern industrial process. This last phase is the basis of such transformation, as the continuous digital interconnection between the business processes and the operational ones of the 'shopfloor' characterizes the innovative factor of any "Smart Factory". The approach is to combine human and machine operations in an amplification of performance and efficiency, always assuring the human centrality in the production processes.
Further, digitalization, associated with the paperless approach, contributes significantly to the sustainability paradigm, seen from the perspective of the process efficiency and, therefore, of keeping lower the environmental impact.

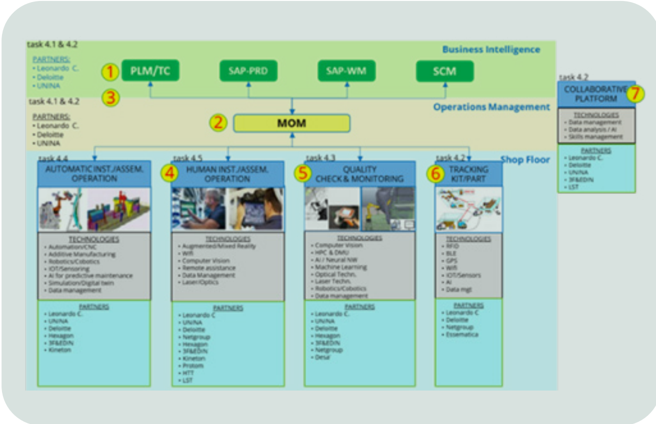


10 – Plant simulation flow [10]



11 – Dashboard of quality KPI and NC locations on 3D map [7]

12 – Workstation operations KPI (ANDON) [7]



13 – Partnership vs digital technologies for Smart Factory [10]

DEVISING TRAINING METHODS FOR HUMAN-BEING VERSUS THE DIGITALIZED PRODUCTION

The activities focus on the planned research and the critical investigation, in order to devise technologies/ methodologies and to find solutions for safe integration of the human factor into the workspace environments of the digitalized factory. The approach consists of devising novel methods to deliver training within the Industry 4.0 framework, by means of the applicable technological & factory pillars, and of assessing the suitability of such "training methods and technologies" versus the human behaviour and the competence/skill growth.

Figure 14 shows an example of the exploration of new training methodologies and/or new applications of the existing training methodology by integrating Virtual Reality and Laser Technologies for certification of the operators for the drilling processes.

The activities include the definition and the characterization of a new role in the organizational charts: the "*Digital Expert*". He is the person who has got the competences and skills needed to manage and guide the changes related to the digital transformation of the production processes.

To reach such goal, it is necessary to set up an upskilling/reskilling process for the acquisition of the new competences/skills/capabilities, to spread them throughout all the organizational levels. In fact, a synergistic approach in terms of hard/soft skill is needed both for management people and for plant operators, as they are required to manage higher degree of automation and digital work environments such as the machine-to-machine and/or man-to-machine ones. The expected results are to integrate more and more man-machine environments in which the human being is in charge to manage the system, while the operational duties at lower added values are left to the machines.

To get these goals, it is strictly necessary to invest in human capital, in terms of developing peculiar professional expertise in Digital Transformation processes in which data are the fundamental measure to understand the organizational phenomena. The consequence is to build up a "*Data Driven Decision Making*" process in which the "*Data First*" mindset is arranged by taking into account techniques for data analytics and for artificial intelligences, to improve both the production processes and the realized industrial products. Within the NEMESI project, the following themes have been prioritized to develop the concerned hard skills of the plant operators:

- Data Driven Approach;
- Data Analysis;
- Data Visualization;
- AI and Machine Learning;
- Digital Twin;
- Additive Manufacturing.

In the meantime it has also been highlighted that the more you grow your professional experience (i.e. your own "*professional baggage*"), the more you need for transforming it into added value for your organization. This concept might be imagined by providing a kind of a "*trolley*" to the plant operators. The "trolley" contains the digital soft skills and the consequent behaviour of the human being. Therefore, in the NEMESI project, the following soft skills have also been prioritized to facilitate the upskill of the personal behavior in a digitalized factory:

- *Analysis Capability and Problem Solution*, which means being able to divide complex phenomena in its essential components, to find out proper solutions. Such skill is one of the most important in a data driven

driven organization in which the critical assessment is needed for visualization and management of the data.
- *Organizational Integration*, means the capability in a "data first" environment to integrate the own professional baggage in the organization to which the person belongs.
- *Flexibility and Availability to Innovation*, means the capability to understand the changes of the organizational environments and to behave consequently by adopting the new solutions based on key enabling technologies, such as Industrial Internet of Things (IIoT), Big Data, Artificial intelligence, etc.

14 – Effective Collaboration Leonardo-Kineton-Hexagon, Digital Twin for Plant Operators [12]

CONCLUSIONS AND LESSON LEARNED

This paper shows the current status of the studies for the NEMESI RDI project, related to digitalization and integration of the factory processes, to realize the Digital Twin of a "full scale" pilot test case related to the ATR fuselage.
This experimentation/assessment of the Key Enabling Technologies and of their integration to achieve the transition to a digitalized factory in the Aerospace & Defense environment, is necessary to find proper solutions in the specific industrial sector of the complex aerostructures, due to specific scale factors and to certification requirements that are not required in other industrial sectors like automotive.
In order to gain benefits from the transition to digitalization of the so-called "Legacy 2D Program" such as the ATR Fuselage, it is necessary to standardize the production processes and to solve uncertainties due both to the digitalization of the aeronautical product and to the system integration of IT architectural environments. However, this depends on HW/SW vendors, too, due to the lack of standardization of their own peculiar solutions. Moreover, in addition to the NEMESI RDI Project and in order to fulfill the certification requirements, dedicated qualification activities are needed for the industrialization of the new experimented technological methodologies in place of the "legacy" ones.
Finally, with reference to the human factor, the transition to the digitalized factory imposes peculiar changes for the development of new skills/competencies and for the organization of the factory, which needs to move from a traditional hierarchic approach to a systemic and interconnected one.

Davide Santoro: davide.santoro@leonardo.com

REFERENCES

[1] https://ec.europa.eu/competition/state_aid/cases1/202346/SA_104370_9078D88B-0000-CE7D-9C8D-45586CF1C918_110_1.pdf

[2] State Aid SA.104370 (2023/N) – Italy Aid to Leonardo S.p.A. for the implementation of the research and development project 'NEMESI', https://ec.europa.eu/competition/state_aid/cases1/202346/SA_104370_9078D88B-0000-CE7D-9C8D-45586CF1C918_110_1.pdf , Brussels, 6.9.2023 C(2023) 6108 final

[3] The Measurement of Scientific, Technological and Innovation Activities, Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, OECD publications

[4] Doc. NEMESI-Leonardo_Hexagon-OR8-T8_1-Convegno_Hexagon_Live-11_11_2024

[5] Proposal for new automation architecture solutions for Industry 4.0, Maicon Saturno, Vinicius M. Pertel, Fernando Deschamps, Eduardo de F.R. Loures, DEStech Transactions on Engineering and Technology Research · January 2018

[6] Doc. NEMESI Deloitte OR4_T4_1-Studio MOM –ERP –PLM Integration –31_08_2023

[7] Doc. NEMESI-Leonardo-OR4-Task4.2-Sviluppi di digitalizzazione e Piattaforma collaborativa -31_08_2023

[8] Doc. NEMESI-Protom_Leonardo_OR4_T4.5_ Sviluppo di SmartUI di Realtà Mista per operazioni di linea_29-9-2022

[9] Doc. NEMESI-Kineton-OR4-T4_1-Approfondimento delle KET e integrazione soluzioni tecnologiche in contesto SmartFactory-31_08_2022

[10] Doc. NEMESI-Leonardo-OR4-D4-Smart Factory-31_08_2023

[11] Doc. NEMESI-Hexagon-OR4-T4_3-controllo qualità-31_08_2023

[12] Doc. NEMESI-Leonardo_Hexagon-OR8-T8_1-Convegno_Hexagon_Live-11_11_2024

Closed-Loop Manufacturing: a Digital Approach to Production

Annamaria Maiorana[1], Becky Piper[2], Lauren Orszt[2], Paolo Grumelli[2], Stefano Pagliai[2], Stefano Vinelli[1]

[1]Leonardo – Corporate/Strategy and Innovation, [2]Leonardo - Electronics Division

Closed-Loop Manufacturing (CLM) has emerged as a critical strategy for driving manufacturing productivity and excellence in the Aerospace and Defense (A&D) industry. This article outlines the key benefits of implementing CLM for A&D manufacturers and offers an overview of how Leonardo Electronics Division has addressed their engineering and manufacturing challenges within the “Future Factory” innovation program.

INTRODUCTION

In the face of escalating complexity in products, processes, and data, the global competitive landscape is undergoing significant transformation. Manufacturers are grappling with key challenges to stay ahead of their peers in meeting consumer demands:

- *Enhancing flexibility*
  Consumers desire personalized products at prices comparable to mass-produced goods. This necessitates manufacturing processes that are more flexible than ever before.
- *Improving quality*
  Consumers reward high-quality products by recommending them online, while poor quality is met with negative feedback. Manufacturers not only have to comply with legal and regulatory requirements, but also meet market expectations.
- *Increasing efficiency*
  Today, sustainability and environmental friendliness are no longer limited to the end product. Energy efficiency in manufacturing and production has become a competitive advantage.
- *Speeding up time-to-market*
  Manufacturers must launch products faster, despite increasing product complexity, to keep pace with rapidly changing consumer preferences. While larger Competitors used to outperform smaller ones, now it is the faster ones that are winning the race.
- *Strengthening security*
  As digitalization expands, manufacturers become more vulnerable to cyberattacks. With data traversing through the cloud, mobile devices, and complex supply chains, implementing robust security measures is essential.

Closed-Loop Manufacturing (CLM) can meet these challenges.

CLOSED-LOOP MANUFACTURING

CLM is the new manufacturing paradigm: new data sources that operate simultaneously, to be connected, integrated and understood in context throughout the value chain of products and manufacturing processes.
CLM allows Companies to harmonize and optimize production across product design, production planning, manufacturing execution, automation, and the insights gained from consumer use.
By establishing a collaborative and connected information loop, CLM continuously enhances the cost, time, and quality of the manufacturing process, speeding up product delivery while maintaining optimal levels of quality and cost. Employing CLM ensures a seamless alignment between the planned product and the actual product, as well as its usage, through an ongoing and iterative process.

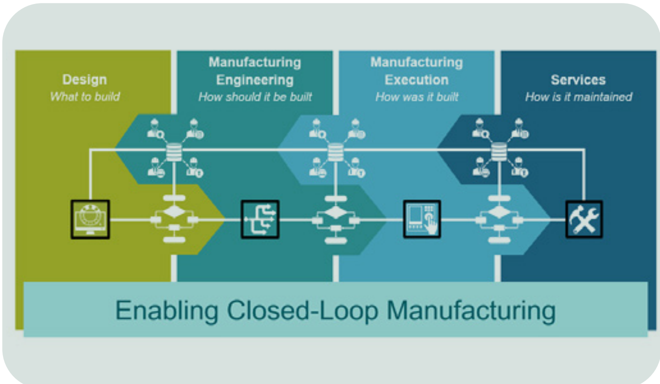
Adopting CLM in Aerospace & Defense

In the Aerospace and Defence industry, the longevity and performance of products are crucial as they need to withstand harsh conditions over many years of service. This makes the design, construction, and maintenance of A&D products exceptionally complex and challenging. Moreover, A&D manufacturers face additional pressures from market trends, further exacerbating these difficulties.
Closed-Loop Manufacturing integrates product design and production engineering with production planning and execution, facilitating bidirectional feedback loops between upstream and downstream processes. This streamlined approach enhances efficiency in activities such as change management and nonconformance tracking and correction. In essence, it provides the necessary speed and flexibility to an industry grappling with unparalleled market complexities.
However, Closed-Loop Manufacturing presents a much needed solution to address these challenges in the demanding business climate of the A&D industry, for all of these reasons:

- Through the orchestration of cross-domain development and engineering processes, CLM's interconnected digital ecosystem effectively handles the amplified complexity and integration of A&D products.
- CLM plays a pivotal role in expediting innovation, thereby enhancing the speed of New Product Introductions (NPIs) and reducing time to delivery.
- CLM provides comprehensive visibility and instant access to all pertinent data, empowering prompt and effective responses.
- CLM plays a vital role in transforming their valuable tribal knowledge into Electronic Work Instructions (EWIs), Augmented Reality (AR) devices, automated processes, and other methods that expedite precise production [1].

Fostering seamless integration in A&D digital transformation

In the past, Companies relied on custom-built solutions to expedite specific functions for specific applications, as digitalization was not yet a mature and standardized technology. Despite the transition of design and engineering domains to digital solutions, the A&D industry continued to rely on paper-based systems for shop floor operations, a practice that today persists in many A&D enterprises due to the relatively low production volumes.
As product lines, production methods, and volumes evolved, Companies adopted point solutions from digital technology vendors as they became available. While these point solutions improved and standardized operations within specific domains, they lacked the ability to seamlessly integrate across different domains. As a result, today the digital ecosystem in many A&D Companies is a patchwork of paper-based systems, internally developed solutions, and point solutions, potentially connected by integrated platforms but limited in scalability due to the complexity of integration.
Closed-Loop Manufacturing offers a solution by providing a cohesive and continuous approach that significantly accelerates accurate cross-domain communication, reduces costs, and enhances productivity, quality, and competitiveness [2].



1-Digitalization in manufacturing -© Siemens

THE IMPLEMENTATION AND IMPACT OF CLOSED-LOOP MANUFACTURING

In the past, digital systems for manufacturing enterprises have traditionally concentrated on one out of three specific technological areas:

- Business Systems such as **Enterprise Resource Management (ERP)** solutions offer information processing and management.
- **Product Lifecycle Management (PLM)** solutions enable product creation and process engineering.
- **Manufacturing Operations Management (MOM)** solutions such as **Manufacturing Execution Systems (MES)** monitor and control production operations.

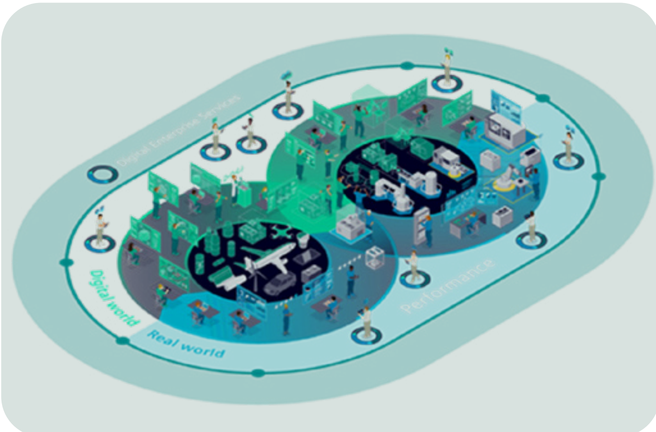
The need for cross-domain data and processes has eroded the traditional distinctions, necessitating the implementation of CLM for seamless continuity.
By integrating the three key domains (ERP, PLM and MOM), often referred to as the "golden triangle", CLM ensures synchronization and optimization across the entire value chain. This includes product design, production engineering and planning, manufacturing execution, shop floor intelligence, and even customer use in the field. Closed-Loop Manufacturing thus provides an Industry 4.0 platform that supports all interactions within the golden triangle. The platform completely digitalizes and seamlessly integrates product and production lifecycles for flexible, scalable production processes. CLM accelerates product development and engineering and maximizes the responsiveness to real-time manufacturing events [2].
Information shared among PLM, MOM and ERP systems includes the following:

- PLM provides the product definition, master process, inspection definition, plant resources and workforce roles and skills to MOM. Moreover, it provides the manufacturing Bill of Materials (mBoMs), part definition and plant resources to ERP.
- ERP provides production orders and the order mBoMs to MOM.
- MOM provides as-built records, order history and status and nonconformance/defect data to PLM as well as production reporting to ERP.

Bridging the gap between engineering and shop floor

Within the realm of Closed-Loop Manufacturing, the bridge between manufacturing engineering and the production floor is one of the most vital connections for Companies in the Aerospace and Defence sector.
Traditionally, once manufacturing engineers have developed the Bill of Processes (BoPs) and operator work instructions for a specific product configuration, these instructions are typically delivered in physical format, often in the form of paper documents, to the production supervisor and team members. The production team then needs to read and comprehend the instructions relevant to their tasks and responsibilities.
However, through the implementation of the digital thread and the adoption of a Digital Twin, A&D Companies can establish a seamless connection between manufacturing engineering and the production floor. This connection allows for the transparent interaction of the Company's Product Lifecycle Management and Manufacturing Operations Management systems.

Consequently, this integration enables the automatic generation of Electronic Work Instructions directly from the engineering-defined manufacturing process [1].



2 – The Digital Enterprise - © Siemens

Effective collaboration between the production floor and engineering teams

The capability to compare the as-built product with the as-designed and as-planned product is a crucial benefit provided by Closed-Loop Manufacturing. Through CLM, raw data generated on the shop floor is aggregated and given context, transforming it into intelligent data that can be shared with designers and manufacturing engineers. The use of intelligent shop floor data not only supports broader initiatives for continuous process improvement but also facilitates immediate actions. In certain situations, production personnel may need to adapt planned processes to align with the actual equipment and capabilities on the shop floor or identify opportunities for improvement while performing their tasks. In such cases, CLM plays a vital role by swiftly notifying designers and manufacturing engineers, enabling them to confirm that the as-built product meets customer requirements. Moreover, with insights from the shop floor, engineers can quickly make adjustments to the as-planned BoPs and EWIs, ensuring that the benefits of these improvements can be realized by the floor team during the next shift [1].

Speeding up the process of introducing new products

When it comes to NPIs and change orders, effective collaboration within a Closed-Loop Manufacturing solution typically begins with the exchange of product or variant information. This information, which is initially defined and created by the design team, seamlessly flows downstream to manufacturing engineers and quality personnel for production planning.
By fostering closer collaboration between design engineering and manufacturing engineering, the time required to bring new products to the market can be significantly reduced. Design engineers have the opportunity to explore various manufacturing scenarios before finalizing a specific design. Similarly, manufacturing engineers can analyse designs early in the development cycle to ensure efficient manufacturability [1].

Continuous improvement

To continually enhance both product designs and manufacturing and assembly processes, Closed-Loop Manufacturing utilizes the knowledge gained from the team's experiences in current and past manufacturing performance through closed-loop feedback.
CLM gathers contextually-relevant data intelligence from various sources, including product, process, machine, people, and business. This data is then utilized in advanced analytics, enabling predictive and prescriptive manufacturing insights and fostering a culture of effective data-driven decision-making [1].

THE FUTURE FACTORY PROGRAM

As part of its Digital Transformation Initiatives, Leonardo has launched, within its Electronics Division, a transnational program called "Future Factory", both in its Italian and UK premises. The CLM implementation is part of the program.

Future Factory vision and mission

The Future Factory Program introduces a technical architecture, and the business enabling processes and operating model across engineering and manufacturing, with full integration across the whole product lifecycle.
The target is to ensure a more robust delivery of products to end customers in time, with quality and within the agreed costs, guaranteeing the sustainability of business in both environmental and economic terms.
The program is structured around the following focus areas:

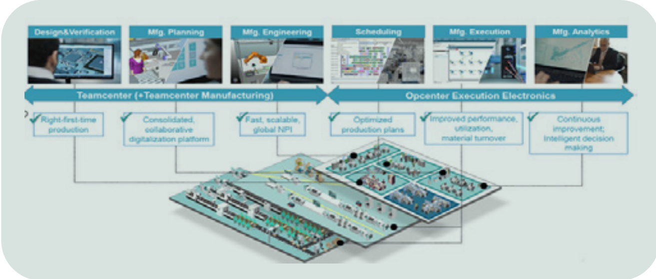
- *Engineering integration*
  Implementing an engineering digital thread connecting PLM, MES, ERP and Requirements Management capabilities, integration of systems and functional engineering data to create end-to-end (E2E) traceability and a single collaborative environment enabling future Digital Twins.
- *Design for excellence*
  New tools and systems to improve product quality and reduce production costs. Enabling engineers to anticipate and resolve potential problems in the design phase ensuring a 'Right first time' production increasing speed of NPI. Integration of PLM and MES to improve control of design and manufacture processes which will enable an improved responsivity to change.
- *Manufacturing Execution*
  Optimized production plans based on equipment resources and skilled operators. Global and plant-wide management to improve visibility of production in order to perform intelligent decision-making.
- *Digital Solutions Drivers*
  Identification of Enterprise Systems to rationalise and standardise toolsets and platforms, building employee expertise of strategic tools, and reducing total cost of ownership. Creating an efficient and secure architecture, compliant with latest standards to provide opportunities for cross discipline integration and a roadmap faster, more flexible deployment.

Within this program, subdivided into different streams including "Digital Engineering" and "Smart Factory", Leonardo has launched important digital transformation projects for the implementation of which the business functions were supported by the Digital Solutions & Engineering function which supported the implementation of the roadmap by guiding the identification and selection of projects in agreement with the business functions, taking care of their governance and supporting their implementation.
As reference platforms for the program implementation, Digital Solutions & Engineering adopted software from the Siemens Xcelerator portfolio from Siemens Digital Industries Software. These solutions focus on:

- PLM (Design to Engineering and Manufacturing Process Planning to Services);
- MOM (Manufacturing Execution, Scheduling, Intelligence).

They are respectively covered by the following platforms, in order to implement the Closed Loop Manufacturing process:

- Teamcenter® software (PLM backbone) and Teamcenter Manufacturing (Process Planning);
- Teamcenter SLM and Opcenter™ software (MES, Advanced Planning Scheduling, Intelligence).



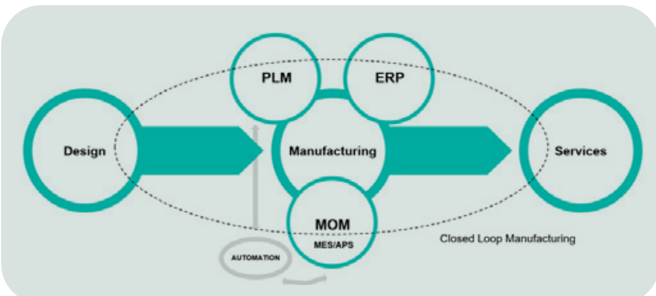
3 – End-to-end electronics manufacturing - © Siemens

CLM adoption and the contribution from Siemens

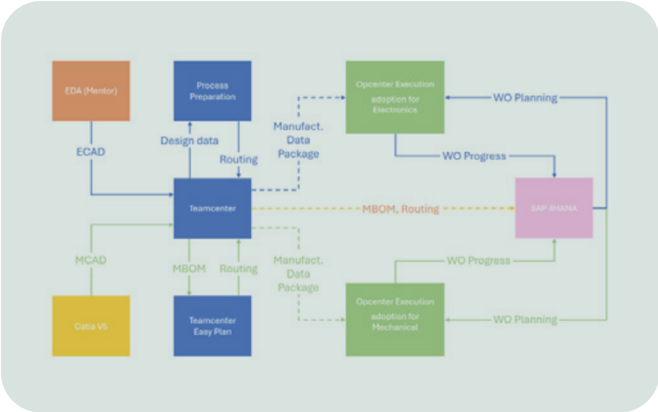
The first objective of implementation is the complete vertical integration of PLM-MOM-ERP (Teamcenter, Opcenter, SAP 4HANA) to ensure closed loop manufacturing.
The goal is to design an overall solution that takes into account the entire E2E process of the value chain of Leonardo Electronics Division and integrates effectively with existing platforms and technologies.
Teamcenter Easy Plan, part of PLM, optimizes plans for the manufacturing process, creates and manages mBoMs and BOPs to understand what to do and how, generates work instructions for the shop floor, performs detailed analysis of operational times, while ensuring close collaboration between engineering teams, production and execution.
Opcenter Execution is a MES software solution that includes manufacturing execution, quality management, planning and scheduling, materials management.
In the Leonardo Electronics Division Italian perimeter (IT), it was necessary to implement two different functionalities, Electronic and Mechanical, due to the different nature of the production processes related to the world of electronic and mechanical machining. In fact, an intrinsic characteristic for a discrete mechanical process is the need to perform sequential and distinct operations for the realization of an assembly: they are successive phases carried out according to a step scheme ("routing") in which each phase corresponds to an action. An electronic process, on the other hand, requires the execution of closely interconnected work phases carried out according to a continuous flow carried out by automatic machines.
The two functionalities are used with the same purpose in different areas:

- Opcenter Execution adoption for Electronics, in the areas of electronic Center of Excellence (CoE), from sorting to final testing;
- Opcenter Execution adoption for Mechanical, in the areas of mechanical and optical CoE, in the box build areas and in the outcoming area.

The final architecture and business processes, starting from the engineering and industrialization of the product, are therefore designed to feed and communicate with the two vertical MES adoptions depending on the production area of reference.
This architecture is not usual but is the result of a specific preliminary analysis phase conducted by Digital Solutions & Engineering function and Siemens in order to define a new reference architectural model that represented the excellence of Leonardo's production departments, both mechanical and electronic, through implementation of the solution that best support the production processes in scope.
Opcenter Execution not only provides MES capabilities and pre-configured capabilities, designed to support the processes of Siemens customers such as Leonardo, but also offers the possibility to extend the solution with low-code applications such as the Mendix™ low-code platform from Siemens and, for example, the addition of role-based features that improve operator efficiency.
The Teamcenter and Opcenter platforms integrate into a digital thread from design and engineering to manufacturing operations that supports the entire product lifecycle by managing manufacturing workflows and providing operator support, advanced electronic work instructions, and quality inspection tools to complete traceability of operations and materials. This enables Leonardo to modify and reconfigure their manufacturing and quality processes to meet growing customer demand and stringent compliance requirements, and to improve their competitiveness in a fast-moving, consumer-oriented market by performing NPIs faster and speeding time to market.



4 – Horizontal and vertical integration - © Siemens



5-Architectural overview

Expected benefits

Such an ambitious program obviously consists of different phases, some of them have already been completed, others are still under development. To date, the "Digital Engineering" stream, both in IT and UK perimeters of Leonardo Electronics Division, is already at a very advanced stage. In particular, in the Italian premises, the integration between design engineering and manufacturing processes has been completed, i.e. the seamless transition between engineering BoMs and manufacturing BoMs. In addition, the solution now guarantees complete control of the product and process configuration, ensuring maximum efficiency of the engineering groups.

In IT perimeter, the introduction of MES in the first plant and the completion of Closed Loop Manufacturing, (planned by early 2025), will allow the full adoption of the solution with a subsequent reduction in NPIs and time-to-market. In the UK the introduction of a modernized engineering toolset is underway with the introduction of an upgraded PLM system and a successful Proof of Concept integrating PLM with both an MBSE and Requirements Management tool.

CONCLUSIONS

The Leonardo approach to ensure Digital Continuity is through the following two dimensions:

- **Horizontal Continuity** in processes supporting the product life cycle (engineering, production, maintenance);
- **Vertical Continuity** in management processes (ERP-PLM-MOM).

The adoption and integration of PLM, MOM, and ERP platforms is therefore crucial to achieve efficient and synergistic management of all phases of the product life cycle and the production process and offers the following benefits:

- *E2E product lifecycle management*
  Management of all phases of the product lifecycle, from design to production, maintenance and market retirement, so that to improve visibility and control over all product-related activities.
- *Reduced product development time*
  More efficient collaboration among design groups, speeding up the product development process.
- *Real-time production optimisation*
  Real-time control of production activities. Monitor plant performance, reduce waste, optimize resource utilization, and improve overall operational efficiency.
- *Integrated enterprise resource management*
  Integrated management of enterprise resources, including machinery, human resources, material procurement, sales, and distribution.
- *Error reduction and quality improvement*
  Error reduction through accurate design data management, real-time traceability, and production control. This helps to improve the quality of the final product.
- *Increased visibility and transparency*
  E2E visibility into all business operations, enabling informed decision-making based on accurate and timely data.
- *Adaptability to market needs*
  Adapt quickly to changing market conditions, thanks to operational flexibility and the ability to respond promptly to customer requests.
- *Reduced operating costs*
  Optimizing operations through integrated planning and control can reduce operating costs while improving the quality and speed of operations.

In summary, vertical integration between PLM, MOM and ERP aims to improve the efficiency, quality, visibility and adaptability of the Company, helping to keep it competitive in a constantly changing business environment.
Closed-Loop Manufacturing can and has achieved new levels of manufacturing productivity and excellence for those A&D manufacturers that are implementing it.

CLM is no longer a nice idea that offers competitive advantages: it is a business imperative!
Closed-Loop Manufacturing can be attained step by step with payoffs all along the way, rather than waiting to complete a multi-year mega-project that pays off only at the end. The key is building an interconnected digital ecosystem on a foundation of robust digital tools, which bring cross-domain capabilities to bear on your operations.

ACKNOWLEDGEMENTS

We thank all the Components of the Leonardo Future Factory Program for the Electronics Division and in particular, Antonio Iannicelli, Daniele Manzo, Francesco Auriemma, Gennaro Esposito, Giorgio Pandozi, Luca Cappelletti, Marianna Radicchio, Roberto De Lucia and Scott McManus. Furthermore, special thanks go to Francesco Rogo e Michele D'Urso for the continuous and effective support of the Future Factory project and for their strong commitment as main sponsors.

Annamaria Maiorana: annamaria.maiorana@leonardo.com
Becky Piper: becky.piper@leonardo.com
Lauren Orszt: lauren.orszt@leonardo.com
Paolo Grumelli: paolo.grumelli@leonardo.com
Stefano Pagliai: stefano.pagliai@leonardo.com
Stefano Vinelli: stefano.vinelli@leonardo.com

REFERENCES

[1] Siemens Digital Industries Software, "The digital future of aerospace and defense manufacturing", © 2023 Siemens
[2] Siemens Digital Industries Software, "Closed-loop manufacturing Using manufacturing operations management to power smart manufacturing", © 2021 Siemens

ViBES: Virtual Based Engineering System

Rocco Gentile[1], Willy Gardiol[1], Pasquale Marino[1], Stefano Centomo[2]

[1]Leonardo - Aircraft Division, [2]Leonardo – Corporate/Strategy and Innovation

The Digital Twin engineering approach in the Digital Engineering environment aims at redesigning the way a system is developed, deployed and supported throughout its lifecycle. In the aerospace industry, the Digital Twin approach faces new and unprecedented challenges. ViBES is the Leonardo solution to the Digital Twin, specifically tailored to needs and peculiarities of Leonardo engineering. ViBES will be a key asset to guarantee digital continuum in the future air power and an enabler to move toward the digital dominance. ViBES will accelerate and make more effective both the concept of new aircraft platforms and the evolution of legacy programs. ViBES is centred on both process and tools development for the Digital Twin, focusing on process improvement supported by the three ViBES platforms: Digital Flight Lab©, SynAPSIS® and MetaSimulator.

INTRODUCTION

This paper aims to report on the latest Leonardo results in the Digital Twin (DT) research area. Due to the topic complexity in terms of methodology and use-cases analysis, it is of keen interest for Leonardo to create a proper and tailored solution that can gather different competences, from different teams, as well as several technical solutions, in terms of models and tools, within a unique Framework. Against such a background, ViBES represents a unique solution. ViBES (Virtual Based Engineering System) represents a proprietary ecosystem based on three Leonardo solutions, for Digitalization of Simulation processes and methods that uses state of the art Model Based System Engineer techniques.

The first paragraph gives a summary about how ViBES has been designed and which needs it aims to solve. The second section reports the overall Goals, ViBES is designed to achieve. The third paragraph describes the pillars of ViBES, including proprietary and commercial off-the-shelf (COTS) solutions. The fourth paragraph describes a typical digitalized simulation workflow in ViBES.

ViBES: VIRTUAL BASED ENGINEERING SYSTEM

Since the first definitions [1]-[3], the Digital Twin was initially conceived as a “mirrored and information spaced model”. This definition already included all the key features of a DT, such as virtual product models and data integration. As noted in [4], in engineering, DT addresses challenges like “analysis paralysis”, where teams work in isolated “silos.” The DT concept offers several advantages:

- It can incorporate multiscale and multi-physics processes to create a “physically coherent twin” of the product, integrating models from different providers into a unified system.
- It enhances model capabilities by leveraging available data, providing a “highly connected organizational framework” [4] that links inputs and outputs across models for the end user.

To build such a platform, several requirements must be met, as outlined in [5] and [6]. Key requirements include:

- **Reusability**: DT solutions should be portable and reusable, supporting a “design once, use many” approach for improved scalability.

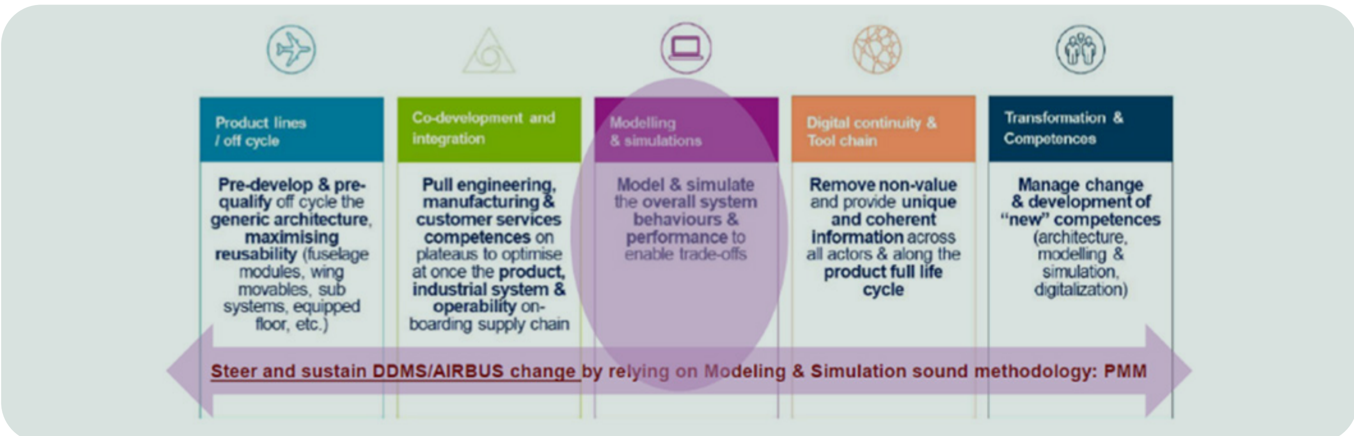
- **Interoperability and Interchangeability**: DT solutions must interact with other DT instances, classes, or end-users, allowing outputs from physical models to serve multiple DT levels, even for non-technical users.
- **V&V Capability**: DT systems must undergo verification and validation before use. Verification checks if a design meets specifications, while validation ensures it meets user needs.

In the aerospace industry, various research teams are assisting aviation companies in developing Digital Twin (DT) platforms [7]. However, due to complexity of the aircraft systems, many studies focus on creating DTs for specific components, incorporating relevant physical models [8]-[11].
The effort required to build a comprehensive DT platform for aerospace has been analysed in [12], which estimates that the U.S. Air Force would need to invest substantial resources, including manpower, time, and funding, to create a fully digital representation of the Next Generation Air Dominance system.
Thus, a more pragmatic approach to DT development is needed that focuses on: the selection of services to provide, the physical assets to represent through virtual models, and especially the methodologies for modelling tasks.
Over the years, several aerospace companies have invested in developing tailored solutions to provide their engineering teams with a comprehensive framework for modelling and simulation, facilitating key Digital Twin tasks [13]. These tasks include:

- **Iterative Optimization**: This design technique relies on an iterative optimization process that refines product specifications from conceptual to detailed design. From a DT perspective, it involves creating models with increasing levels of detail to enhance accuracy and efficiency, aiding in product selection. Additionally, it leads to evolving sets of parameters and specifications that can be tracked across the product lifecycle.
- **Data Integrity**: Addressing the "silos" problem, this task ensures the consistent integration of fragmented component knowledge among stakeholders. The DT continuously collects, analyses, and accumulates data from the physical environment to support the decision-making during the design phase. This process involves challenges such as data digitalization, collection from diverse sources (both structured and unstructured), and data cleaning and extraction.
- **Virtual Validation & Verification**: During the design phase, DTs enable multidisciplinary interaction between systems and their future operating environments without incurring additional costs. This allows engineers to verify and validate requirements, identify and resolve issues, and test components in unpredictable scenarios.

A notable example of such a framework is Airbus's Digital Design, Manufacturing & Services (DDMS) platform. This initiative aims to deliver a comprehensive end-to-end process, spanning from preliminary design to final assembly, with the objectives of reducing costs and time to market, while ensuring high standards of quality, safety, and environmental performance. As shown in Figure 1, the physical modelling of aircraft systems plays a key role in supporting the entire product lifecycle.

However, despite the DDMS represent a remarkable outcome of an ambitious project in cooperation with important software houses (such as MathWorks and Dassault Systemes), it is not based on in-house solutions that can be both fully tailored on the necessity of Engineering teams and fit the legacy processes that characterize the complex design phases of aircraft systems.
Within this framework, ViBES represents the in-house Leonardo solution as digital ecosystem, based on proprietary company technologies, that allows to digitalize the design phases according to the state-of-the-art MBSE techniques.



1-Airbus DDMS project process

ViBES PILLARS

As previously mentioned, ViBES is founded on three main proprietary Leonardo technologies:

- **Digital Flight Lab© (DFL)**: collaborative environment that digitalizes the MBSE design process. It drives different users through the overall set of collected data regarding the models under investigation: from the relative requirements to the simulation results in certain conditions. As collaborative environment, the DFL allows different users with different privileges according to the relative need-to-know principles, to explore the relative modelling information with different levels of granularity: from system-of-systems to component, according to the project hierarchy to provide. The DFL is a cloud-native solution that can be easily deployed in different Leonardo infrastructures: from the Davinci-1 to local deployment in specific facilities, such as Restricted Areas.
- **SynAPSIS®**: proprietary integration platform that constitutes the Aircraft Division Synthetics Simulation core. Through the years, the SynAPSIS® integration platform has been consolidated as the simulation orchestrator that is core for all the Leonardo Aircraft Division (LAD) training simulators, from Procedural Training Devices (PTD) to Full Mission Simulator (FMS). It is based on the concept of distributed data exchange, advanced scheduling supporting several standards of communication, both commercial and aviation protocols. Within ViBES, SynAPSIS® is the orchestrator engine which runs the models stored in the DFL. Exploiting SynAPSIS® as the simulation core allows to drastically reduce the transition from the Model development to the deployment of an Aircraft simulator.
- **MetaSimulator**: parametric platform that can be tuned to represent any kind of air vehicle for development purpose. MetaSimulator is composed by a set of typical aircraft systems that can be parametrized to behave accordingly to the use-case under test. In ViBES it allows the final user to have a generic aircraft configuration that can be used as testing environment for the model to develop.

Starting from these technologies, ViBES has been designed to have all the necessary interfaces with standard legacy off-the-shelf solutions such as Modefrontier for optimization task, CAMEO and Rhapsody for SySML modelling, Ansys Twinbuilder for reduced-order modeling etc...
The following Table reports a comprehensive list of already integrated and planned MBSE software, and the current relative integration status. In the next paragraph, a design workflow for the complete toolchain is presented.

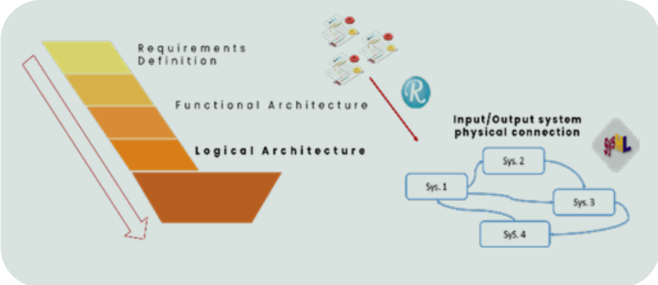
Tool	Proprietary
SynAPSIS®	Leonardo
Digital Flight Lab©	Leonardo
MetaSimulator	Leonardo
IBM Doors NG	COTS
IBM Rhapsody	COTS
DASSUALT CAMEO	COTS
Matlab / Simulink	COTS
Simcenter Amesim	COTS
Esteco Modefrontier	COTS
Ansys TwinBuilder	COTS

Table 1–ViBES list of supported modelling tool

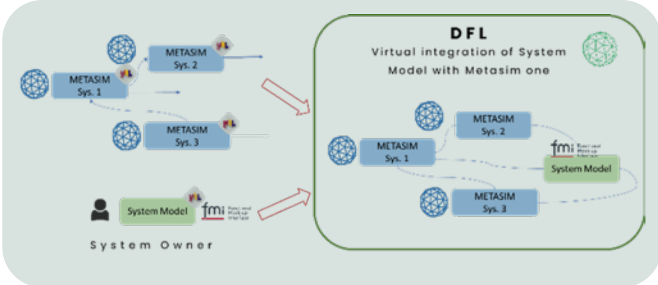
DIGITAL MBSE DESIGN WORKFLOW

As noted in [14], the effectiveness of a product's DT in the industrial sector relies on fidelity of its simulation. In this context, to enable DT capabilities, it is essential to connect models based on various physical attributes.
For example, using a multi-physical model as the core of a DT allows engineers to measure real-time physical quantities that are otherwise difficult to detect in the real world.
At Leonardo, there is a need for virtually replicating the behaviour of a complex, integrated system, incorporating models from diverse disciplines such as aerodynamics, flight dynamics, structural analysis, thermodynamics, electric propulsion etc...
To achieve this goal, the implemented workflow in ViBES includes:

1. **Requirements definition**: system requirements are collected and defined by using tools such as IBM DOORS-NG tool, ensuring traceability and linkage to specific parts of the project.
2. **Model-Based Systems Engineering (MBSE)**: designers use UML/SysML tools (such as IBM Rhapsody or Cameo) to create models of aircraft subsystems, defining architecture and behaviours, which are then verified and validated against the requirements in DOORS. The output of this step is then uploaded in the DFL platform that can create the simulation template for each defined system and recreate the connections between the blocks, according to physics-based modelling. This step is fundamental to ensure the connection between the upper-level architecture and the physical-based modelling.



2-Workflow step 1 and 2

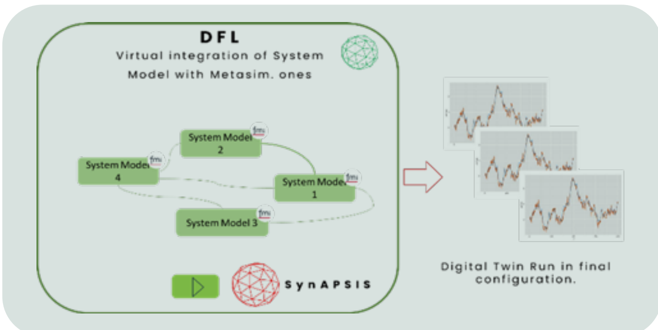


3-Workflow step 3 and 4

Figure 2 reports the classic Request-Functional-Logical-Physical (RFLP) modelling technique of the MBSE methodology that represents a starting point for the design workflow in ViBES.

3. **Design and development**: the SysML models uploaded in DFL can be easily examined by each system specialist, exactly retrieving all the necessary information of the relative model to develop, such as: Input to require, Outputs to provide and Parameters to specify accordingly to the system physics. Afterwards, each specialist can perform the relative modelling task by using appropriate Model-Based Design (MBD) tools, such as Simulink, AMESIM, Dymola depending on the specific task.
4. **Digital Twin building**: the models are then exported from the MBD tools according to the Functional Mockup Interface (FMI) standard and they get integrated in the DFL platform. The FMI standard ensures great flexibility in terms of MBD tools to use and other technical model specification, such as relative mathematical solver. Once the system model is exported as a Functional Mockup Unit (FMU), it is ready to be uploaded in DFL. Figure 3 schematically represents the typical integration between a FMU System Model and the MetaSimulator blocks. The SysML logical architecture, exported at the end of step 2, can be easily populated with available MetaSimulator blocks that need to be tuned accordingly, to connect with the imported FMU model. In this way, the System Owner is able to test the model with a predefined Aircraft architecture, for a rapid outcome. Moreover, the MetaSimulator represents an important library of predefined models that can constitute the initial structure of the overall Digital Twin.
5. **Digital Twin run**: modularity of the MetaSimulator allows to use its models as plug-and-play blocks that can be easily replaced by other refined System Models from other Owners. This flexibility and the multi-user availability of the DFL, allows different System Owners to perform the relative model test and build step-by-step the Digital Twin structure, based on high-fidelity system models. Once the Digital Twin has reached the desired level of physical fidelity, it is possible to setup in DFL the simulation setup and execute it through SynAPSIS®. As reported in Figure 4, just by clicking the RUN simulation button, the DFL converts automatically the information regarding the blocks connection into the necessary Interface Control Document (ICD), including all the information about models inputs, outputs and parameters, and execute SynAPSIS® in background for the overall fixed simulation time. Afterwards, the DFL collects all the simulation results from SynAPSIS® and expose them in a dedicated Simulation registry that can be easily explored by the team members and each System Owner.
6. **Design Optimization**: once the baseline Digital Twin structure has been successfully built and executed, the design process can be considered complete when the model performances are in line with the final performance requirements that can require additional tuning and analysis. These Optimization task can be performed in ViBES thanks to its integration with specific tool, such as ModeFrontier. These particular analyses allow the ViBES users to explore different configurations and improve system performance for final Requirements V&V.

This six-step design workflow represents the baseline use of ViBES framework for digital design with the current supported toolchain of interfaced software (Table 1). However, it is important to emphasize that ViBES features continue to evolve according to new design standards to implement and promising tool to integrate. For instance, the development team is conducting several studies regarding the integration with Simulation and Process Data Management (SPDM) solutions, with Data-Lake infrastructure for model and simulation results storage and, last but not least, with AI-tools to create Reduced order Models from high-fidelity simulations.



4-Workflow step 4

ACRONYMS

COTS: Commercial-Off-the-Shelf
DDMS: Digital Design, Manufacturing & Services
DFL: Digital Flight Lab
DT: Digital Twin
FMI: Functional Mockup Interface
FMS: Full Mission Simulator
FMU: Functional Mockup Unit
ICD: Interface Control Document
LAD: Leonardo Aircraft Division
MBD: Model Based Design
MBSE: Model Based System Engineering
PTD: Procedural Training Devices
RFLP: Requirements, Functional, Logical, Physical modeling
SPDM: Simulation Process and Data Management
ViBES: Virtual Based Engineering System
V&V: Validation and Verification

CONCLUSIONS

In conclusion, ViBES provides the tools and guidelines to develop a Leonardo focused process to design a Digital Twin for an aircraft or a system of an aircraft.
By leveraging the collaborative functions of the Digital Flight Lab©, the involved engineers can collaborate in the development of the Digital Twin. By using the SynAPSIS® integration platform, the various stages of the development from prototype to Digital Twin can be deployed esily on different, scalable, target systems, while being them integrated once for the entire lifecycle.
The MetaSimulator provides a parametric platform to leverage the early development phases in which the aircraft models are at an early stage of development.
Through these tools, it is possible to digitalize the operative design workflow based on MBSE techniques, valorising the legacy company knowledge in terms of modelling and simulations.

Rocco Gentile: rocco.gentile@leonardo.com

REFERENCES

[1] M. Grieves e J. Vickers, «Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems», in Transdisciplinary Perspectives on Complex Systems, F.-J. Kahlen, S. Flumerfelt, e A. Alves, A c. di Cham: Springer International Publishing, 2017
[2] M. Grieves, «Origins of the Digital Twin Concept», 2016, doi: 10.13140/RG.2.2.26367.61609.
[3] S. Flumerfelt, K. G. Schwartz, D. Mavris, e S. Briceno, A c. di, Complex Systems Engineering: Theory and Practice. Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2019.
[4] D. J. Wagg, K. Worden, R. J. Barthorpe, e P. Gardner, «Digital Twins: State-of-the-Art and Future Directions for Modeling and Simulation in Engineering Dynamics Applications», ASCE-ASME J Risk Uncert Engrg Sys Part B Mech Engrg, vol. 6, n. 3, set. 2020, doi: 10.1115/1.4046739.
[5] Q. Qi et al., «Enabling technologies and tools for digital twin», J. Manuf. Syst., ott. 2019, doi: 10.1016/j.jmsy.2019.10.001.
[6] J. Moyne et al., «A Requirements Driven Digital Twin Framework: Specification and Opportunities», IEEE Access, vol. 8, 2020, doi:10.1109/ACCESS.2020.3000437.
[7] H. Meyer, J. Zimdahl, A. Kamtsiuris, R. Meissner, F. Raddatz, e S. Haufe, «Development of a Digital twin for Aviation Research», n. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference., pag. 9, apr. 2012.
[8] G. Bachelor, E. Brusa, D. Ferretto, e A. Mitschke, «Model-Based Design of Complex Aeronautical Systems Through Digital Twin and Thread Concepts», IEEE Syst. J., vol. 14, n. 2, giu. 2020, doi: 10.1109/JSYST.2019.2925627.
[9] F. Cappuzzo, O. Broca, S. Vouros, I. Roumeliotis, e C. Scullion, «Application of Model Based Systems Engineering for the Conceptual Design of a Hybrid-Electric ATR 42-500: From System Architecting to System Simulation», in Volume 1: Aircraft Engine; Fans and Blowers, Virtual, Online, set. 2020, pag. V001T01A027, doi: 10.1115/GT2020-15329.
[10] E. J. Tuegel, A. R. Ingraffea, T. G. Eason, e S. M. Spottswood, «Reengineering Aircraft Structural Life Prediction Using a Digital Twin», Int. J. Aerosp. Eng., vol. 2011, doi: 10.1155/2011/154798.
[11] H. Cai, W. Zhang, e Z. Zhu, «Quality Management and Analysis of Aircraft Final Assembly Based on Digital Twin», in 2019 11th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), Hangzhou, China, ago. 2019, doi:10.1109/IHMSC.2019.00054.
[12] T. D. West e M. Blackburn, «Is Digital Thread/Digital Twin Affordable? A Systemic Assessmentmof the Cost of DoD's Latest Manhattan Project», Procedia Comput. Sci., vol. 114, 2017, doi: 10.1016/j.procs.2017.09.003.
[13] P. Aivaliotis, K. Georgoulias, Z. Arkouli, e S. Makris, «Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance», Procedia CIRP, vol. 81, 2019, doi: 10.1016/j.procir.2019.03.072.
[14] J. Wu, Y. Yang, X. Cheng, H. Zuo, e Z. Cheng, «The Development of Digital Twin Technology Review», in 2020 Chinese Automation Congress (CAC), Shanghai, China, nov. 2020, doi: 10.1109/CAC51589.2020.9327756.

Editor in Chief
Vincenzo Sabbatino

Editorial office
Emidio Di Pietro
Giovanni Cocca
Marco Morini
Patrizia Pozzoni

Published and Printed by:
Leonardo S.p.A.
Innovation
Piazza Monte Grappa, 4
00195 Roma

The Editorial Team thanks Daniele Dragoni
for serving as the Guest Editor, and Danilo Defant and Paolo Casanova for their contribution.

The POLARIS Innovation Journal is an editorial initiative of the Chief Innovation Office.
Other initiatives of the POLARIS Innovation Journal are the Paperbacks and the Lunchtime Webinars.
The Journal invites questions and suggestions from readers.
Contact the Editorial Office at: polaris@leonardo.com

Scan this QR code to access the web version

https://www.leonardo.com/polaris_2025_52/

In compliance with the Leonardo sustainability policies,
and to contribute reducing the environmental footprint of the Company,
the POLARIS Innovation Journal is printed on certified paper (Xerox International Certificate).
The POLARIS Innovation Journal is published biannually.

Issue 52 – February 2025