Digital Twin/Digital Thread Solution Definition for Aerospace and Defense: Phase 2

Problem, Objectives, Proposed Definitions, Go Forward

Release 1.0

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AEROSPACE & DEFENSE PLM ACTION GROUP

Abstract

The Aerospace & Defense PLM Action Group (AD PAG) collectively sponsored a team of domain experts from AD PAG member companies to define objectives, requirements, and roadmaps for digital twin/thread solutions.

In Phase 1 the team conducted research that identified a plethora of digital twin/thread concepts and definitions. A method of describing this phenomenon was prepared to organize and understand the definitions. In support of preparing the A&D industry's digital twin/thread definitions, the team prepared constructs to describe the intended functionality and utility of the digital twin/thread. The resulting A&D industry definitions are the collaborative work of representatives from several leading A&D companies.

This Phase 2 project deliverable is a digital twin/thread position paper for the A&D industry. The purpose is to facilitate an industry baseline definition and understanding of the current capabilities of the digital twin/thread in the A&D industry.

NOTE: Contributions were provided by industry domain experts, each representing their company's perspective. Therefore, differing perspectives exist within this document. Retaining these perspectives substantiates the objectives of this paper, which are to define a framework to rationalize the differing perspectives and, more importantly, to reach a consolidated objective and definition of the digital twin/thread concept.

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Revision Record

Release	Date	Description
1.0	**July 2022**	Initial full release of the research-based position paper that states the problem, outlines objectives, provides proposed digital twin/thread definitions for the A&D industry, and includes a Go Forward Plan. This paper is the Phase 2 deliverable of the AD PAG Digital Twin/Digital Thread project.

Digital Twin/Digital Thread Solution Definition for A&D

Executive Summary

The Aerospace and Defense Product Lifecycle Management (PLM) Action Group (AD PAG) is an association of aerospace Original Equipment Manufacturers (OEMs) and aircraft engine manufacturers within CIMdata's globally recognized PLM Community Program, which functions as a PLM advocacy group. The AD PAG has sponsored a project team of domain experts (also known as SMEs, *subject matter experts)* from the member companies to define objectives, requirements, and roadmaps for digital twin/thread solutions for creating and managing the digital representation of a product through the various stages of the product lifecycle.

This project is designed to be executed in multiple phases. Seven phases are proposed, each with a specific objective and associated deliverable. Each phase builds upon the knowledge and deliverables of the prior phase(s). The deliverable of Phase 1 was a literature search of documentation intended for internal use by the project team in support of the Phase 2 work. The principal deliverables of Phases 2 through 7 are publicly released position papers.

- Phase 1 – Research – Examination of existing industry digital twin/digital thread technical literature
- Phase 2 – Digital Twin/Digital Thread Solution Definition for Aerospace and Defense
- Phase 3 – Digital Twin/Digital Thread Business Architecture/Methodologies
- Phase 4 – Digital Twin/Digital Thread Comparative Analysis of Industry Standards
- Phase 5 – Digital Twin/Digital Thread Value Proposition
- Phase 6 – Forward-Looking Digital Twin/Digital Thread Strategy and Roadmap
- Phase 7 – Digital Twin/Digital Thread Project Consolidation

A summary of the Phase 2 findings follows:

- Multiple digital twin/thread definitions exist, and these definitions are influenced by business, system, and technical perspectives.
- The commonality and uniqueness of digital twin/thread definitions can be grouped by product lifecycle phase. A company's participative role in the aviation or A&D industry influences the value and utility of the digital twin/thread.
- An industry-defined ontology and taxonomy are needed for the definition, decomposition, and composition of the digital twin/thread.
- The generalized approach observed in defining digital twin/thread is to treat the digital twin and the digital thread as separate and distinct initiatives that are collectively addressed under the aspect of the digital enterprise.
- Variation exists in the purpose and use of the digital twin/thread across the product lifecycle.
- Digital twin/thread interoperability standards are required to fully realize the value of the digital twin/thread.

Introduction

In March 2021, executives from the AD PAG member companies – Airbus, Boeing, Embraer, Gulfstream, Pratt & Whitney Canada (P&WC), Rolls-Royce, and SAFRAN – met to review and approve a proposed special project. They agreed to sponsor a project team of domain experts from the AD PAG member companies to define objectives, requirements, and roadmaps for digital twin/thread solutions for creating and managing a product's digital representation through the various stages of the product lifecycle.

The AD PAG Digital Twin/Digital Thread team's first workshop was held at the beginning of Q3 2021. The project team's charter defines seven phases to define and produce a series of sub-projects and associated deliverables to be executed over the course of two years.

Phase Two

The AD PAG team's Phase 2 goal was to produce this *Digital Twin and Digital Thread Solution Definition for Aerospace and Defense* position paper. This phase leverages the learning from the Phase 1 research, denotes digital twin/thread definitions, identifies initial digital twin/thread use cases, and releases this position paper for review and consideration within the A&D industry.

NOTE: Contributions were provided by industry domain experts, each representing their company's perspective. Therefore, differing perspectives exist within this document. Retaining these perspectives substantiates the objectives of this paper, which are to define a framework to rationalize the differing perspectives and, more importantly, to reach a consolidated objective and definition of the digital twin/thread concept.

What is the requirement for another position paper to define digital twin/thread? An aspect of this paper that makes it unique is its presentation of the **interrelationship of the digital twin and the digital thread**. Other aspects of this position paper include the following:

- Describe the digital twin and digital thread from a high-level perspective.
- Define the main characteristics of the digital twin, digital thread, and digital product (i.e., the design intent of one part, one system, or one sub-system. Digital product is described in the *Digital Twin/Thread Interaction Example* section).
- Define the main characteristics of the interface between the digital twin and digital product.
- Define the prerequisite of the approach for the digital twin, digital thread, and digital product (e.g., data structure/quality, etc.).
- Put definitions into the context of the product lifecycle and business, system, and technical perspectives.
- Expand the definition of the digital twin to include systems, processes, and services.
- Define the collaborative and interdependent relationship between the digital twin and the digital thread.

A thorough discussion regarding digital twin/thread/product business requirements will be addressed in the AD PAG Digital Twin/Digital Thread project team's *Digital Twin/Digital Thread Business Architecture/Methodologies* paper (to be released in Phase 3 of the project).

Approach Overview

As a starting point, the team researched, identified, and discussed the following topics:

- Multiple digital twin/thread definitions that exist within the A&D industry
- Principal role of the digital twin
- Principal role of the digital thread
- Varying viewpoints of the digital twin/thread
- Method of organizing digital twin/thread definitions
- Definition of the A&D digital twin
- Definition of the A&D digital thread
- A&D integrated digital twin/thread

Problem Statement

A plethora of digital twin/thread position papers and associated definitions exists within the A&D industry. (*Appendix A* provides a list of prominent publications.) From an industry perspective and specific to digital twin management throughout the product lifecycle, this position paper attempts to reconcile definitions, unify differences, and construct a formal framework of industry definitions.

Digital Twin/Thread Position Paper: Purpose and Objectives

The purpose and objectives of this digital twin/thread paper are to provide an understanding of the need that digital twins and digital threads are intended to fulfill. The variability of need provides a foundation for understanding why several acceptable definitions for digital twin and digital thread exist.

Digital Twin

Several variations of purpose and objectives for the digital twin and associated definitions are described as follows:

- The digital twin of a physical asset can provide data about the physical status of the object, such as its physical state and disposition. Conversely, a digital object may be used to manipulate and control a real-world asset through teleoperation (Markets, Research and, 2020).
- A digital twin is an exact virtual copy of an object, system, or process. The role of the digital twin continues to expand in manufacturing and supply chain management, ranging from specific equipment to entire business ecosystems. Digital twins are created using data derived from the Internet of Things (IoT) sensor technologies attached to or embedded in the original object or system (Crawford, M., 2021).
- A digital twin is a virtual representation of a physical product, asset, process, system, or service that allows us to understand, predict, and optimize its performance for better business outcomes. The

role of the digital twin in advancing industrial operations, especially production and predictive maintenance, is highly significant (Madni, Azad, et al., 2019).

Figure 1 illustrates the uses of the digital twin throughout the product lifecycle.

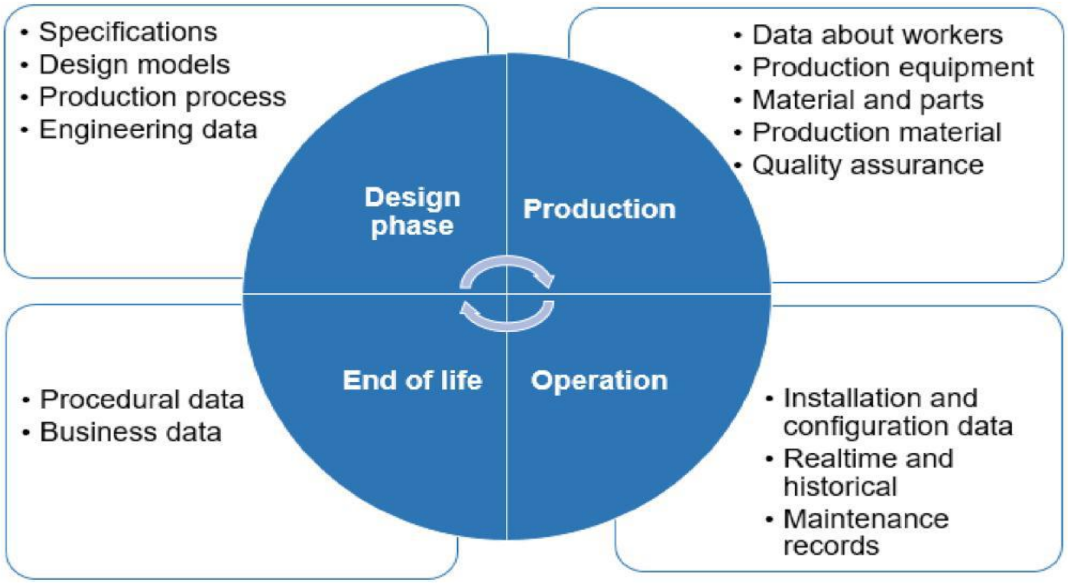

Figure 1 - Uses of Digital Twin in Product Lifecycle Management (Melesse et al., 2020)

Digital twin technology has been regarded as a beneficial approach in supply chain development. Different from traditional digital twin (temporal dynamic), a supply chain digital twin is a spatiotemporal dynamic system.

A digital twin may be a composition (system) of one or more digital twin components. A taxonomy is required to organize the aggregation and decomposition of a digital twin.

Digital Thread

Several variations of purpose and objectives for the digital thread and associated definitions are described as follows:

- The digital thread enables the merging of the physical and digital worlds. With a digital thread, users can analyze and forecast the performance and optimization of their products. The digital thread and associated functions are interconnected, integrated, and linked so users can quickly access, share, and manage programs. A digital fabric aligns with the most commonly used functional programs: engineering, program management, supply chain, production, and product support (Siemens Digital Industries Software, 2020).
- The digital thread is a communication framework that allows a connected data flow and integrated view of an asset's data (i.e., its digital twin) throughout its lifecycle across traditionally siloed functional domains. The viability of the digital thread extends beyond the intended applications used to establish the thread. This raises the importance of using a standards-based approach in defining, using, and managing the digital thread in support of cross-enterprise thread sharing through the product lifecycle (CIMdata, 2020).

- The purpose of the digital thread in manufacturing is to modernize the engineering dispositions of non-conformances in production by integrating data, models, and analysis tools to provide engineers with actionable information for rapid dispositions, process re-engineering, and serial-number-specific lifecycle management (Kobryn & Boden, 2017). This same concept can be extrapolated and applied to the products' lifecycle's operational phase, providing actionable information to the aerospace industry crew and ground operations team.

Definition Framework of the Digital Twin/Thread

One challenge the team encountered early in the Phase 1 research was the numerous digital twin/thread definitions. The team identified three viewpoints that represent views of how digital twins/threads are used: business, system, and technical. When aligned with the product lifecycle phases, a matrix is defined. Each cell provides an opportunity for a unique definition. The team did find commonality in definitions. These are identified by color groupings within the matrix.

Commonality and Uniqueness of Digital Twin/Thread Definitions

Through research and discussions, the project team identified and categorized the differences in the description and utilization of the digital twin/thread. Those differences reflected the organizational value and terminology used by a particular organization. A distinct difference in the perspectives was represented by the business, system, and technical views. The project team recognized that the product lifecycle phase also presented variations in terminology and value. In addition, the methods, tools, and systems used contributed to differing views and associated value.

The Basic Framework

The framework shown in the following figure (Figure 2) consists of three rows and eight columns. The rows represent views from a business, system, and technical perspective. Each column represents a phase of the product lifecycle. The Supplier column represents an Original Equipment Manufacturer (OEM) perspective relative to the part or component produced by a supplier and integrated into the manufactured product. The inclusion of this Supplier column elevates the importance of the supplier and the supply chain's digital twin/thread contribution to the OEM and to the customer/user/owner/operator within the A&D ecosystem.

Digital Twin/Thread Definition Framework

		Supplier	OEM				Customer/User/Owner/Operator		
		Part/ Component/ Material	Requirements	Design	Engineer	Manufacture	Operation	Maintenance	Disposition
Business	Artifacts								
System	Models and Data								
Technical	Tools and Methods								

Figure 2 - Digital Twin/Thread Definition Framework

Digital Twin Framework

The following figure (Figure 3) provides a visual representation of the common and distinct **digital twin** terminology used to describe the digital twin. The color coding represents digital twin definition commonality in how the digital twin would be applied. For example, the blue coloring represents common terminology from a system engineering perspective—terminology that is utilized in the requirements, engineering, and manufacturing PLM phases. The operation, maintenance, and disposition PLM phases have an operational perspective of the digital twin and use a different set of terminology. The intensity of the color represents where the primary system view of the digital twin perspective originates.

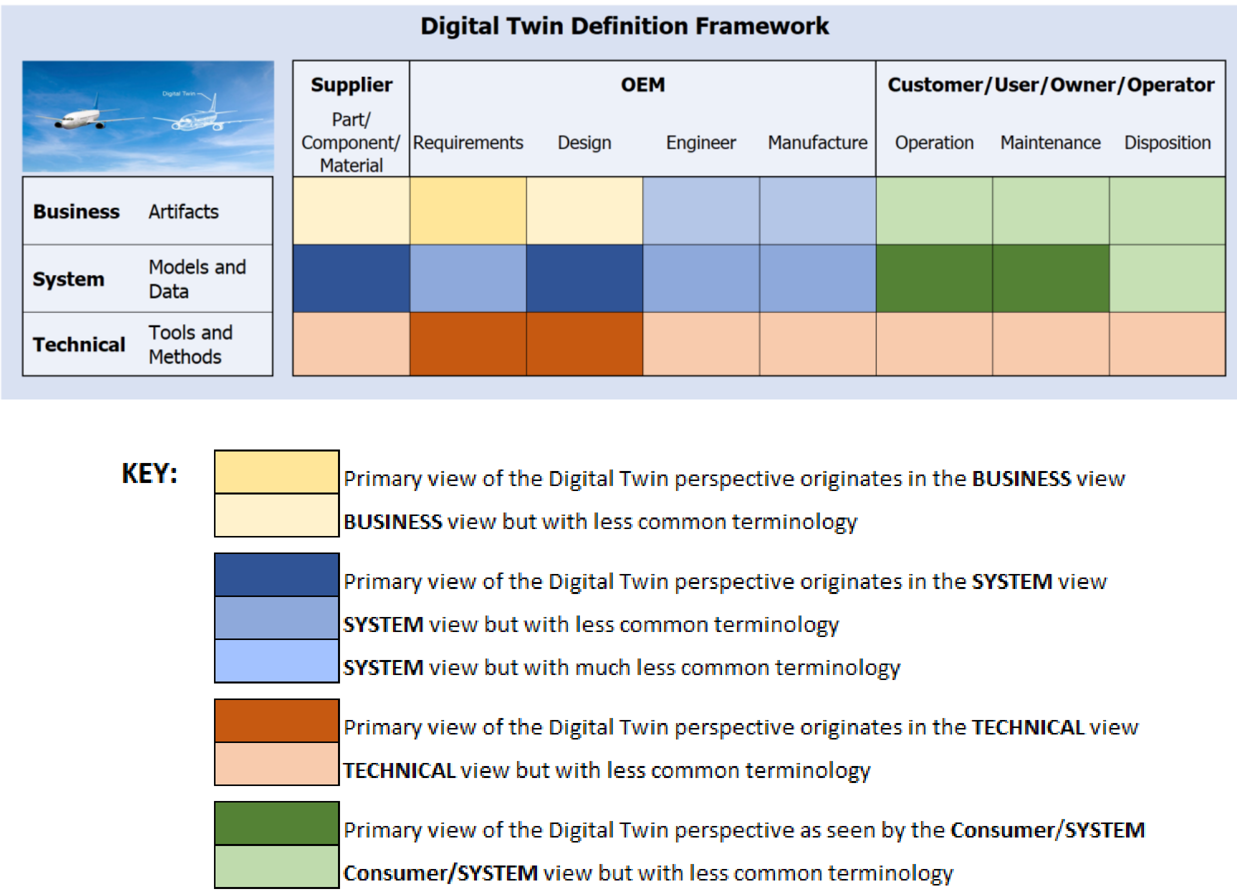

Figure 3 - Digital Twin Definition Grouping

Digital Thread Framework Grouping

Applying the framework to the definition of the **digital thread** produced a significant difference from the representation for the digital twin in a view and purpose perspective (see Figure 4). The colors represent grouping of common definitions. The expected commonality of definitions across the business, system, and technical rows was not found. What was found is an increased discord in purpose. The major contributor to this is the way data and information are defined and used by organizations and across the product lifecycle. The understanding and application of digital thread is less mature than that of the digital twin. This indicates a requirement for greater emphasis on leveraging an organization's data definition/management in defining the purpose and value of the digital thread.

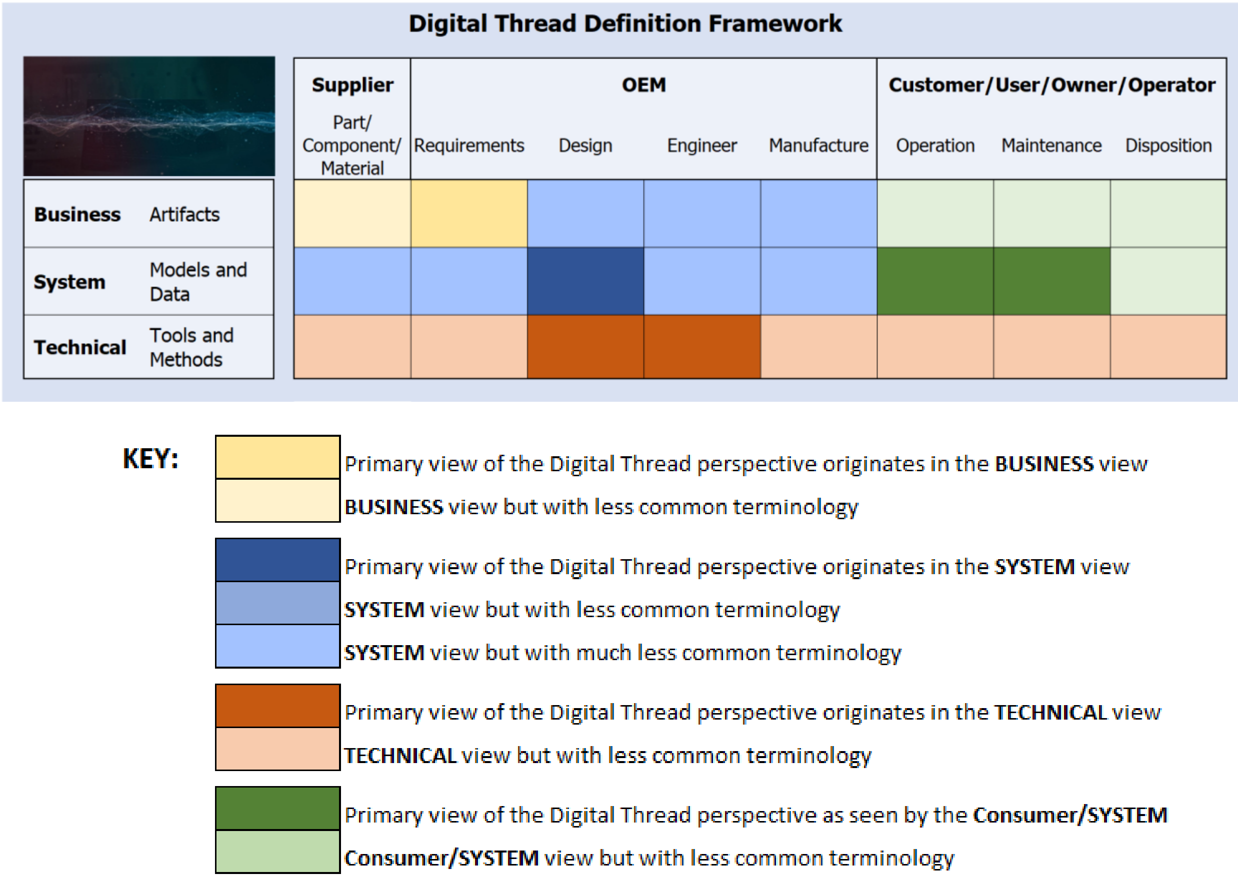

Figure 4 - Digital Thread View/Purpose Grouping

PLM Viewpoints of the Digital Twin/Thread

The concept of having multiple digital twin/thread viewpoints and descriptions was just introduced in the framework sections. The following is a discussion of these multiple viewpoints across the product lifecycle.

Business Perspective

This section summarizes the business perspective of the digital twin/thread.

Digital Twin

From the business perspective, the digital twin allows for the integration of the theoretical view of the product/system with the view of the observed physical product. This facilitates digital verification and confirmation of change to the physical entity throughout its lifecycle. The digital twin helps calibrate and correct the theoretical model. The benefit of this capability is a limited[1]

[1] Limited due to the lack of information to fully understand the behaviours and abilities of the digital twin without the digital thread. Therefore, assumptions regarding waste reductions can be estimated only.

reduction in waste throughout the product lifecycle, resulting in improved productivity, planning, delivery, service, and decommissioning.

Digital Thread

The digital thread provides the ability for a business to have an Authoritative Source of Truth (ASOT), which is information available and connected in a core set of enterprise systems across the lifecycle and supplier networks. The benefit of this capability is that the business can produce products correctly the first time, ensuring waste reduction and providing improved services due to real-time product monitoring. This will substantially reduce the cost of manufacturing products and increase service revenues.

System Perspective

A system represents the business' function as a whole. Product lifecycle phases represent the following functional domains within the system:

- **Concept phase:** Regarding the product, the industrial system that will manufacture the product or operation system (of the product). This domain is often linked (I)MBSE – MDAO (Multi-Disciplinary Analysis and Optimization) – Trades
- **Design/Definition phase:** Usually this domain is covered by the PLM domain and tools; the aim is to make official and store the definition of the product and the industrial system
- **Manufacturing phase:** This is the start of execution. Step-by-step the product becomes real; this domain of information is shared between Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES)/Manufacturing Operations Management (MOM)
- **Operation phase:** This is a follow-up of the product in its usage by the customer; this domain of information is covered by Customer Resource Management (CRM)

Considering a digital twin, each phase could focus on one or several points of view.

Digital Twin

Based on the context defined previously, a digital twin is a specific viewpoint during one phase where a center-of-interest representation is built. The digital twin is built with the use of data provided by the digital thread, information from domain systems (e.g., PLM, ERP, and MES) and from real-time data obtained from the physical object.

With the rapid development of Smart manufacturing, production management challenges are emerging. These include the use of information technology and the elimination of dynamic manufacturing disruptions. The industrial system digital twin of production management can dynamically simulate and optimize production processes in manufacturing and facilitate real-time synchronization, increasing product fidelity and enabling real-time transparency of physical production. Industry 4.0 introduced the integrated use of information communications technology and a cyber-physical system to support decision-making in Smart production and manufacturing. As such, the real-time interactions required between the physical layer and information layer are difficult to achieve. The cause is a lack of real-time statistics and dynamic feedback between the physical and informational platforms. Consequently, abnormalities are not discovered, diminishing the ability to adjust quickly during the production process and in the operational environment. To remotely monitor machines and analyze energy consumption and product quality information, a Digital-Twin-driven Production Management System (DTPMS) is needed to establish real-time synchronization between the physical world and the digital world. The DTPMS covers the entire production life cycle including product design, product manufacturing, and intelligent service management (Ma, J., Chen, H., Zhang, Y. et al. (2020).

Digital Thread

Based on the hypothesis described earlier, the digital thread integrates models and data in a common functional domain. This could be accomplished through different methodologies. Semantic integration is one possibility for which Information Management/Information Technology (IM/IT) capabilities are well known, and the associated tools are well developed.

The digital thread is a data-driven architecture that links information from all stages of the product lifecycle (e.g., early concept, design, manufacturing, operation, post-life, and retirement) for real-time querying and long-term decision making. Information contained in the digital thread may include sufficient representation of available resources, tools, methods, and processes, as well as data collected across the product lifecycle (see Figure 5).

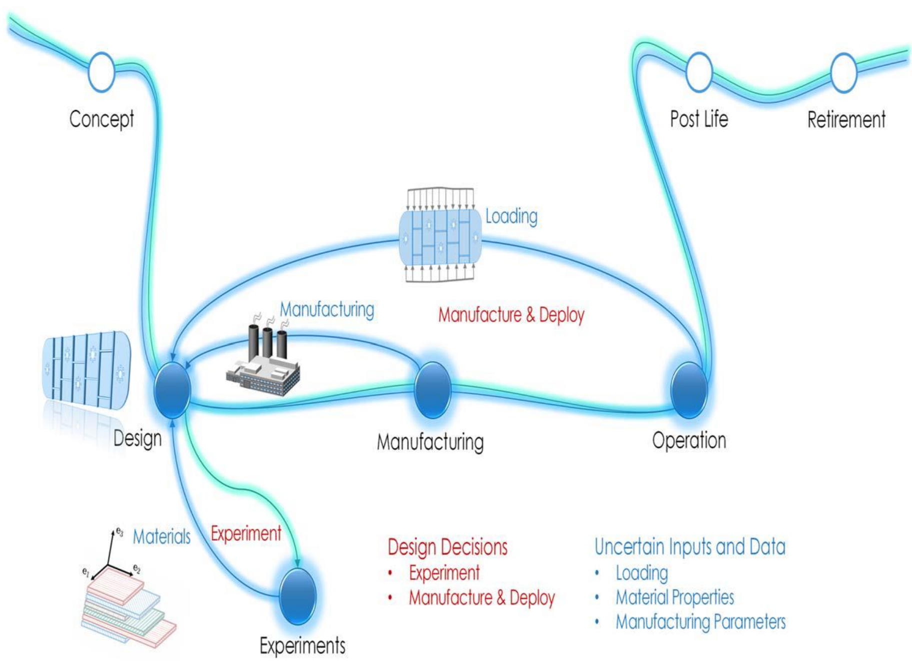

Figure 5 - Illustration of the Digital Thread for Example Design Problem - The Product Lifecycle (Singh & Wilcox, 2021)

A relatively unexplored aspect of the digital thread is how to represent and understand the propagation of the uncertainty within the product lifecycle. High levels of uncertainty can lead to designs that are overly conservative or designs that may require expensive damage-tolerance policies, redesigns, or retrofits if analysis cannot show sufficient component integrity. One way to reduce this uncertainty is to incorporate data-driven decisions informed from data collected throughout the design process. The digital thread can be seen as a synthesis and maturing of ideas from PLM, MBE (Model-Based Engineering), and MBSE (Model-Based Systems hEngineering).

Despite the range of development and growth of digital thread and its application to manufacturing and maintenance/operations, a digital twin system that considers the propagation of uncertainty in the product lifecycle in the context of the digital thread is sparse. In addition, a way to analyze and optimize sequential data-informed decisions as new information is added to the digital thread remains absent.

A digital thread system must consider the digital thread as a state that can dynamically change based on the decisions made and how data is collected. The evolution of uncertainty within the product lifecycle can be represented in the digital thread itself. The evolution of the digital thread can be modeled as a dynamical system that can be controlled using a dynamic program where the objective is to minimize total accrued costs over multiple stages of decision-making (Singh & Willcox, 2021).

Technical Perspective

This section approaches the digital twin/thread topics from the engineering design theoretical framework, the PLM lifecycle, and the potential practical implementation perspective.

It is understood that the digital twin, as a virtual representation of a real thing, must be enabled through a representational formalism and communication framework that allows for a common multi-disciplinary, end-to-end connectivity. That is the digital thread.

When it comes to the digital twin/thread, product models and the related theory of domains are better suited to encapsulate the concepts and develop methodologies for practical implementations in the context of the existing product lifecycle management assets, technology, and proven benefits. To that end, it is important to first frame the domains which consist of the conceptual framework that can support developing methodologies and tools for the practical implementation of the digital twin/thread.

Digital Twin

The capture/representation of physical prototypes or “In-Service” serialized artifacts is rarely addressed in the theory of domains, design, and product structuring literature. The physical domain discussed in the literature consistently refers to the embodiment of a design artifact (i.e., engineering definition), which does not belong to the realm of the resulting tangible and serialized instances (Experimental/Operations/Service).

Männistö et al. (2001) highlighted the contrast by stating that “data structures suitable for manufacturing are not the most appropriate for after-sales. After-sales requires its own concepts, and its information must be presented in a view of its own.” Multiple serialized instances of the same system (“As-Designed,” i.e., physical domain) may exist in the field or during test rig experimentations with the corresponding performances and potential failures recorded at the serialized component and build configuration level. This is of special importance in the case of companies providing products as service or “uptime” plans (Männistö et al., 2001). The type of view (e.g., serial instantiation, allocation, build configuration, data gathering, and performance tracking) and the array of information required to be structured in the context of this domain is different from the physical domain as it is referred to in the existing literature. Drawing upon explorations, findings, and recommendations from Glaessgen & Stargel, 2012; Tao et al., 2017;

and Toche, 2017, it is proposed to extend the functional, technological, and physical domains to include a new *existential* domain, reflecting builds and traceable instances of a technical system.

Customer/User/Owner/Operator View

From the view and purpose framework grouping, this perspective is linked to the operation, maintenance, and disposition phases of the product lifecycle. Typical value drivers associated with this perspective are maximizing overall equipment effectiveness and reliability and minimizing turn-around time, maintenance costs, and/or time needed to troubleshoot problems in the field.

Digital Twin

The counterpart of the handover of the physical asset from the OEM to the operator is the transition from “As-Built” digital twin to “As-Operated” and “As-Maintained.” This raises the question of duplication and/or continuity of the digital twin along the Sale process.

Regarding fleet management, a trend associated with the digital twin as a service is platforms or portals for aircraft and engine health monitoring. Remote data collection and analytics are key to yielding intelligence that will enable quicker and better decision making in the areas of maintenance work scope, inventory supplies, and end-of-life aid.

Another benefit of digital twin, which could be linked to the visual interpretation and visual consumption use case that will be described in a future document of this team’s project, is reduced workforce training time (e.g., contextualizing inspections using both 3D DMU (Digital Mock-Up) and either a tablet device or Augmented Reality (AR) goggles). In this context, digital twin as a Single Source of Things (SSOT) also promotes the diffusion and knowledge of the latest technical publications.

Digital Thread

As more data is produced downstream in an asset’s lifecycle and as more parties are involved in the PLM challenges of integration, interoperability and ownership increase. This leads to the question of whether the digital thread should pragmatically also be a composite of various threads even though it could mean dismissing the additional value that could stem from translation of operation to requirements for future products (i.e., closing the feedback loop).

Digital Twin/Thread Definitions for A&D

The following digital twin/thread definitions reflect the consolidated contribution of project participants and the knowledge gained from the A&D industry. Each definition is followed by a list of constructs used in preparing the respective definitions.

The Digital Twin

This section includes the digital twin definition for A&D, highlights the elements in the literature that contributed to the definition, and provides a concept example from the literature.

Definition

A digital twin is a virtual representation of a physical entity, its behaviors, and the associated processes used to create it. This includes the concept and design phases of a product or system development. It is an integration of data from various sources (i.e., digital thread) that defines a future, existing, or historic item, system, process, or service and operational environments. Such representation, augmented with field data, provides a means of visualizing, understanding, predicting, and optimizing various aspects of the physical entity's design and behavior, as well as its fabrication, assembly, and the environment in which it is/was/will be used, maintained, and disposed of. Ultimately, a digital twin is expected to experience every event that its physical twin experiences, and it can be used to explore situations that a physical twin has not yet experienced.

Contributing Elements from Industry Research

The following examples are representative of many characterizations and partial definitions which were drawn from the project team formulating their proposed digital twin and digital thread definitions. Various levels of a digital twin are illustrated below (Figure 6).

For example, the digital twin can be applied at different levels including component, asset, system,

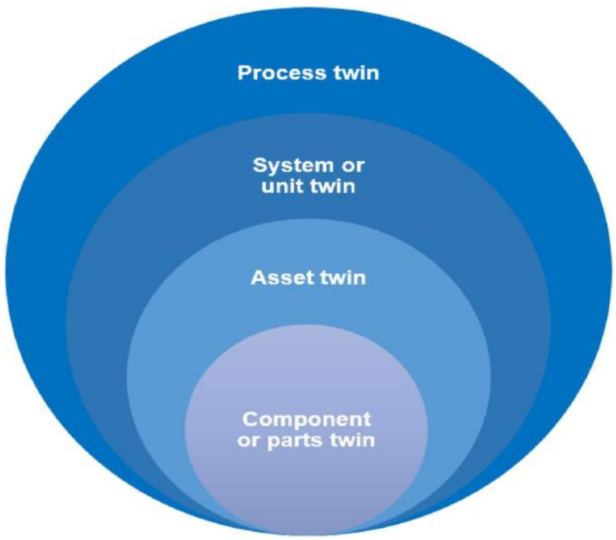

Figure 6 - Levels of a Digital Twin (Melesse et al., 2020)

or unit, or as a process twin (Melesse et al, 2020). The component twin is a representation of a major part of assets that have a significant impact on the operation of the system. The asset twin focuses on the entire assets. Collecting these assets will create a network of system or unit twins that provides visibility in a set of different types of equipment.

- The digital twin is a modeled definition of an existing, future, or historic object, system, process, or service (Crawford, 2021; Melesse et al., 2020; Madni et al. 2019).
- The digital twin is comprised of one or more modeled objects (Kraft, 2018; Madni et al. 2019; AIAA Digital Engineering Integration Committee, 2020).
- The digital twin is designed, engineered, manufactured, maintained, and disposed of following industry standards and design practices (Melesse et al., 2020).
- The digital twin facilitates the ability to understand, predict, and optimize an object, system, process, or service (Kraft, 2016; Madni et al. 2019).

- The digital twin utilizes digital threads to receive information and to transmit data to and from the object, system, process, or service to provide awareness and knowledge over the entire lifecycle of an object, system, process, or service (Kraft, 2018).
- The digital twin is operationalized utilizing Industry 4.0/X.0 information technology capabilities.
- Industry 4.0/X.0 integrates the digital twin with the actual physical system utilizing sensor data and software to monitor both the digital twin and the physical object (Melesse et al., 2020).
- The purpose, utility, and value of the digital twin varies in definition throughout the object lifecycle.

Concept Examples from Technical Literature

The digital twin and digital thread are interactive elements of the lifecycle representation of the system. The digital twin is initiated from early descriptions and models of the airframe developed and preserved in the digital thread. The digital twin assessment of the "As-Built" aircraft during production is drawn from engineering data in the digital thread. Similarly, the simulation of aircraft operations used in the digital twin for analysis emanate from predictive flight models and flight records captured in the digital thread. The update to the digital twin "As-Maintained" aircraft during sustainment is drawn from maintenance records in the digital thread. Overall, the configuration of the digital twin is controlled through the digital thread (Kraft, 2016).

The Digital Thread

This section includes the digital thread definition for A&D and highlights, through example, the elements in the literature that contributed to the definition.

Definition

The digital thread is a communication framework that enables connected data flows for the integrated view of lifecycle artifacts and their resulting asset's data (i.e., digital twin) across traditionally siloed functional product lifecycle domains. This communication framework depends on standardized, model-based representations and semantic data modeling to facilitate the dynamic creation of context, based on multiple viewpoints. As the asset is produced, operated, maintained, and progressed through its lifecycle stages, the digital thread fabric is continually expanded to holistically merge the digital and physical worlds.

Contributing Elements from Industry Research

The following examples are representative of the many characterizations and partial definitions present in the technical literature, which were drawn from by the project team in formulating their proposed digital thread definition. An example representing the complexity of the digital thread is shown below (Figure 7).

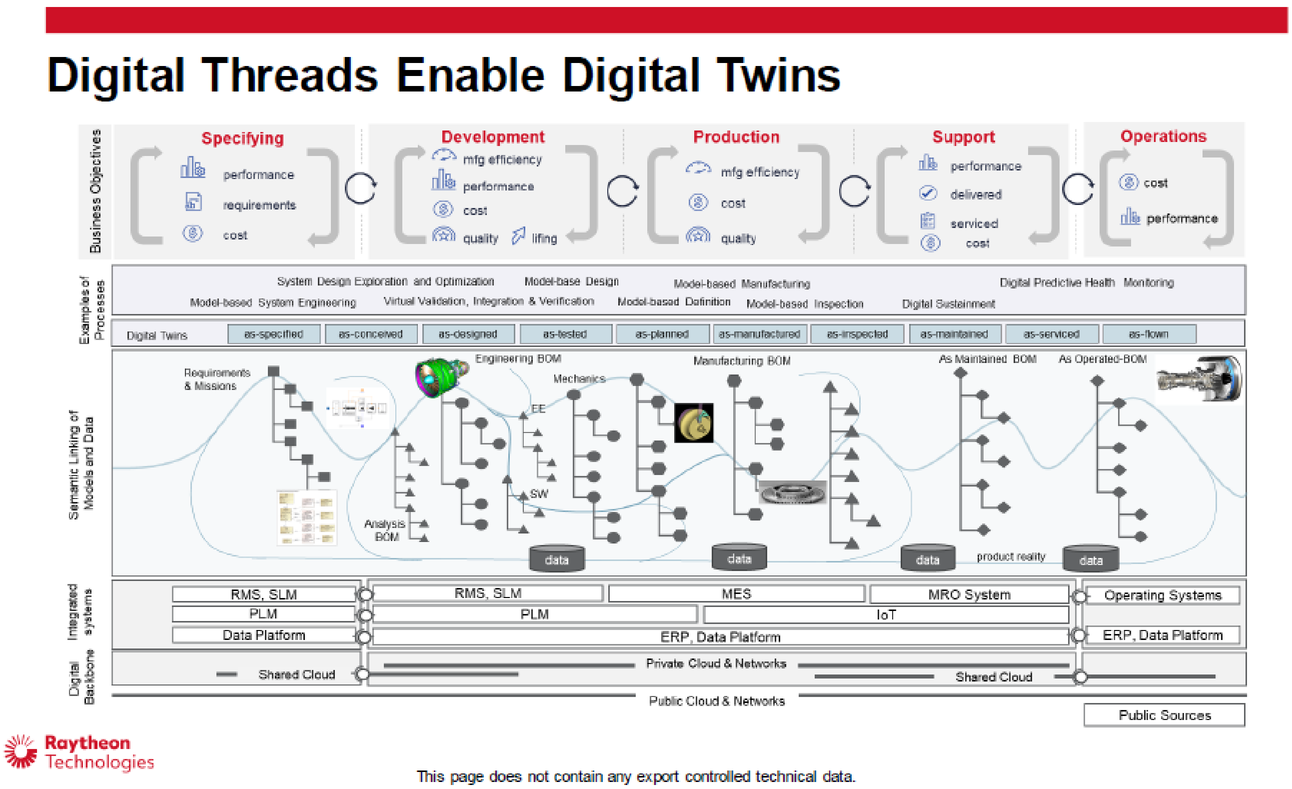

Figure 7 - Digital Thread (Alberto Ferrari, Sr. Director Raytheon)

- The digital thread enables the merging of the physical and digital worlds. With a digital thread, users can predict performance and optimize their products. The digital thread and associated functions are interconnected, integrated, and linked so users can quickly access, share, and manage programs. A digital fabric aligns with the most commonly used functional programs: engineering, program management, supply chain, production, and product support (Siemens Digital Industries Software, 2020).
- The digital thread is a communication framework that allows a connected data flow and integrated view of an asset's data (i.e., its digital twin) throughout its lifecycle across traditionally siloed functional domains. The viability of the digital thread extends beyond the intended applications used to establish the thread. This raises the importance of using a standards-based approach in defining, using, and managing the digital thread in support of cross-enterprise thread sharing across the product lifecycle (CIMdata, 2020).
- The purpose of the digital thread in manufacturing is to modernize the engineering dispositions of non-conformances in production by integrating data, models, and analysis tools to provide engineers with actionable information for rapid dispositions, process re-engineering, and serial-number-specific lifecycle management (Kobryn & Boden, 2017). This same concept can be

extrapolated and applied to the product lifecycle's operational phase, providing actionable information to the aerospace industry crew and ground operations team.

- The digital thread links disparate systems across the product lifecycle to support data curation and information cultivation and enable data-driven applications (e.g., digital twin). Realization is that the digital thread requires integrating semantically rich open standards to facilitate the dynamic creation of context based on multiple viewpoints (Helu, M. et al., 2018).
- Digital threads are static (linear) and dynamic (non-linear). The dynamic characteristics of digital threads are defined and managed by models representing the associated use, value, and origin (Accenture, 2021).
- Digital Fiber–Digital Fabric. The digital thread is comprised of digital fibers, and a digital fiber is the fundamental unit of the digital thread. The digital fiber may represent data attributes or characteristics of the digital thread. The aggregation of two or more digital fibers defines the characteristics of a digital thread. The digital thread is dynamic, meaning the purpose or utilization of the thread can have one or more uses. The definition of the digital thread requires a definition of the digital fiber characteristics/parameters that facilitate the dynamic nature of the digital thread (Hummell, 2017; Immerman, 2022; Miklovic, 2021).
- An organizational structure does not bind a digital thread definition and utilization. The implications of this are that digital threads will be defined/composed by one or more entities' companies (i.e., a multi-company/government definition of a digital thread). Establishing the need for industry participation in defining the digital thread (Ferrari & Nagel, 2020).
- The digital twin is dependent upon one or more digital threads as the method of acquiring and disseminating data/information (Singh &Willcox, 2021).
- The digital thread exists without the obligation of a digital twin (Ferrari & Nagel, 2020).

Interdependent Digital Twin/Thread

The generalized approach observed in defining the digital twin/thread is to treat the digital twin and the digital thread as separate and distinct concepts that are collectively addressed under the aspect of the digital enterprise. However, the interdependency of the digital twin and the digital thread is increasingly recognized as necessary to the digital product and to improve the digital twin's integrity and value proposition. The research approach used to determine this interdependency involved a search for published digital thread papers that included the term *digital twin*. The digital product is enabled through the modeled orchestration of the interdependent relationship of the digital twin and digital thread.

- According to Kraft (2018), the purpose of the digital thread is to link disparate systems across the product lifecycle and throughout the supply chain. This concept of linking systems is more than the physical and telecommunication linking, and this linking includes functional decision-making and data interoperability across the product lifecycle. A specific example is a lifecycle information framework that explains how linked, contextualized, certified, and traceable data provided by the digital thread enables data-driven applications such as the digital twin (Kraft, 2018).
- In contrast to the lifecycle, information framework is the challenge of managing data from different PLM systems. The heterogeneity of these systems limits the ability to establish an ecosystem-standards-based digital thread solution. The effect is a focused emphasis on engineering models and not on the need for knowledge sharing between various functions across the product lifecycle

(Kraft, 2018). Kraft (2018) defines the need for integrated knowledge over the entire product lifecycle, from design to final disposition.

- Siemens (2020) defines the relationship of the digital twin and digital thread as the ability to leverage the full potential of a digital twin, to maximize its ability to think and understand the impact of changes from one connected twin to another or from one connected system to the next within the product development ecosystem. This type of functionality requires a powerful, integrated, and continuous exchange of digital information. This is the role of the digital thread. In other words, the digital thread provides the bi-directional connectivity of data, information, and knowledge of the digital twin.

Digital Twin/Thread Interaction Example

There can be as many digital twin forms as there are needs and uses. An "As-Designed" digital twin will not have the same information as an "As-Built" digital twin, although the "As-Built" is issued from the maturation of the "As-Designed" state. In the same fashion, the "In-Service" state results from a maturation of an earlier state in the product lifecycle. Therefore, as a manufacturer moves through the lifecycle states, the quantity of available information increases. The business value stream activities will determine which data is utilized.

To help clarify the different states of the digital twin, it is important to differentiate the intent of digital twins from the "As-Designed" digital twin to the "As-Disposed" digital twin.

- The intent of the "As-Designed" digital twin is to address all the physical assets in a virtual representation like a 3D model, a set of specifications, or an aerodynamic or a thermal computation, which will be referred to as a *digital product*. A digital product is the design intent of one part, one sub-system, or one system. It includes (but is not limited to) elements, such as initial designs with available trade-offs, that support justification for the design, requirements from the upper level to the lower level, architecture models, Failure Mode Effects and Criticality Analysis (FMECA) Digital Mock-Up (DMU), simulations, certification reports, and maintenance documentation (Madni, Azad, et al., 2019).
- The "As-Built" digital twin is a virtual definition of the digital product. This means that a digital twin is a representation of the available physical asset. Therefore, each asset can be virtually represented by a digital twin, as long as a digital thread is available to provide required data.

The following two figures (Figures 8 and 9) illustrate that the digital thread enables the linking of one or more digital twins to the digital product. In strictest terms, there is no direct link between the digital product and associated digital twins.

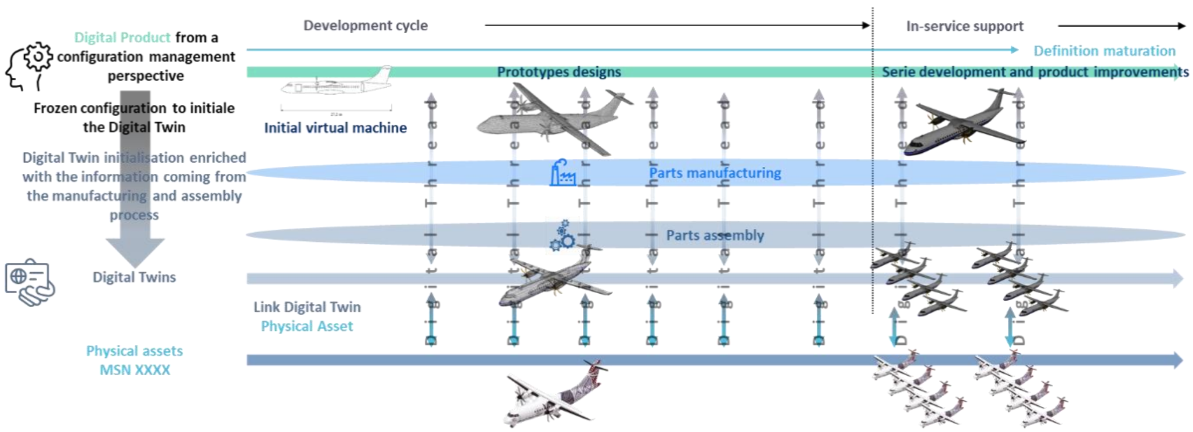

Figure 8 - Digital Product, Digital Twin, and Digital Thread (Soulie, S., 2022)

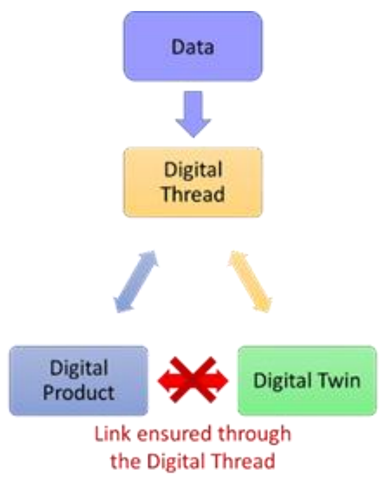

Figure 9 - Links between the Digital Product and Its Digital Twins (Soulie, S., 2022)

A digital thread has all the means necessary to generate, register, and distribute the data associated with a part, sub-system, and system. The digital thread is as large and varied as is its creator's interest in information feedback. However, several referenced and governing rules must be defined (to be addressed in Phase 4 of the project) to manage the data. Then, it will be possible to link the data to the digital twin. It is necessary to do the following to maintain the value of and interest in the digital twin:

- Structure the digital thread.
- Define the "authoritative source" of data.
- Characterize the type of the data and define.

A digital thread is not sustainable in the long term without a data governance policy. The "As-Built" digital twin must also be defined. The "As-Built" digital twin is a representation of the "As-Built," "As-Maintained" configuration that can be produced throughout the lifecycle of the product, from the very beginning of the project (it starts with the very first drafts) to end of life and product disposal.

The digital twin aims to provide all the definition information available throughout the product lifecycle. As indicated earlier in the digital product reference, for a given configuration, all or parts of elements may be content, depending on the needs expressed by digital twin users.

There are different objectives for a digital twin. Starting at the "As-Required" state, it will allow the aggregation of the design proposal versus the customer requirement, keeping traceability of the decisions made to find the best compromise solution. Utilizing experience from a previous project, if correctly defined, can be part of the decision criteria. As an example, a digital twin allows the following use cases:

- Being able to improve the design of new products coming to market by considering the capability of how a given product requirement definition behaves in service
- Being able to reconcile quickly and with high quality the overall compliance of given upstream design requirements

Considering the "As-Designed" phase, a digital product is key to accelerating design iterations in response to customer specification revisions. At this step, being able to represent a physical asset, sub-system, or system by virtually describing its material characteristics, operating conditions, or assembly status is key to increasing the number of iterations to optimize a design by eliminating the need for physical tests and demonstrations. During this phase, the same kind of simulation can be performed by the manufacturer to address the ability to forge, cast, machine, etc. the part as the designer defined the object. Working with a digital twin also allows logistical support analysis to prepare for maintenance conditions. Ultimately, a digital twin is key to quickly optimizing a product to transform it from an idea to a sustainable concept by enabling rapid feedback loops between all stakeholders.

Once the design is available for manufacturing, it is possible to start creating digital twins by aggregating data generated during manufacturing and all the associated measurement acquisitions. It then allows the following activities to occur:

- Being able to confront digital product assumptions versus reality
- Verifying a number of engineering use cases' computations of a set of configurations, such as load computation, mass computation, and performances computations
- Having an extended understanding of a non-compliance during the manufacturing or assembly process and having the corresponding impact analyses
- Identifying potential manufacturing process savings by optimizing machining trajectory, process capability, cutting tools durability, and manufacturing tools improvements

The digital product is not only an artifact that allows the digital twin to emerge as an initial structure that can be enriched by all the data that makes the twin alive but also a concept that allows manufacturers to “freeze” the digital thread on a particular picture that represents a given enriched configuration.

Taxonomy and Ontology Requirements for Digital Twin/Thread Definition and Use

The team discovered the use of the terms *digital twin* and *digital thread* could be defined as a company objective, strategy, or future capability. From an executive leadership perspective, the term *the digital twin* or *the digital thread* evokes the sense of a broad, holistic concept similar to the popular term *digital transformation*. Achieving digital transformation requires the orchestration of systems, methods, standards, and capabilities. And the same is true for achieving a digital twin or digital thread.

To extrapolate and understand the composition of a digital twin and/or thread requires the ability to logically decompose the digital twin and digital thread through a taxonomy that identifies the components and subcomponents and maintains the functional relationship of objects during the decomposition. The reverse is also true as the respective digital-twin-defined elements of a digital twin are aggregated into a composite digital twin.

While both the decomposition and composition of a digital thread may be similar, the characteristics and relationships of the digital thread utilize a different taxonomy structure. This is a function of the independent or autonomous relationship between the digital twin and digital thread.

Proposed Use Cases for Digital Twin/Thread

This section provides an introduction of use cases that will be evaluated and demonstrated in Phase 5. The proposed business values are:

- Use Case 1: Supply chain from the perspective of product design development and information exchange between design organizations, production of part production, fulfillment, and specification compliance at installation
- Use Case 2: Factory operations optimization, manufacturing feature-based machining (i.e., integration of the factory digital twin optimization with product digital twin production)
- Use Case 3: OEM submission of Technical Data Package (TDP) to authority for certification
- Use Case 4: Product operational performance monitoring and predictive performance validation
- Use Case 5: Visual interpretation and visual consumption

Digital Twin/Thread and Global Collaboration

A major business challenge of the AD PAG Global Collaboration team is to achieve OEM and supply chain collaboration through bi-directional exchange of Technical Data Packages via standards-based integrated digital tools and model-based processes. This integrated, standards-based, global collaboration-based strategy enables the Digital Product Authoritative Source of

Truth. The team's Phase 3 *Digital Twin/Thread Business Architecture/Methodologies* paper will define this Digital Product Authoritative Source of Truth.

Go Forward Plan

Using the framework defined in this paper, the future Phase 3 *Digital Twin/Thread Business Architecture/Methodologies* paper will propose a business architecture and associated methodologies required to incorporate and utilize digital twin/thread concepts within the A&D industry.

The concepts presented in this Phase 2 paper will be reviewed and identified for inclusion into that *Digital Twin/Thread Business Architecture/Methodologies* (Phase 3) position paper. These concepts include the following:

- The Why?
  - Definition of the business value/competitive impact of digital twin/thread to the A&D industry as defined by the AD PAG
  - Business value definition that digital twin/thread brings to the A&D ecosystem, including the supply chain and development partners
- The What?
  - Consistent definition and alignment of the digital product with the digital twin/ thread
  - Digital Product Authoritative Source of Truth - An aggregation of truthful authoritative sources within the aviation and aerospace industry ecosystem
  - Definition and ranking of the highest priority digital twin/thread application use cases by the AD PAG Digital Twin/Digital Thread team members, based on potential business impact/return on investment (ROI), and scope/stage(s) of the lifecycle
  - Determination of which enterprise organizations and partners need to be involved
- The How?
  - Definition of a digital twin/thread functional and technical roadmap for the AD PAG's highest priority use cases
  - Definition of product lifecycle digital twin/thread business objects
  - Definition of the digital twin/thread business reference architecture
  - Definition of the required IoT and IT architecture and tools
  - Definition of the required product lifecycle management reference architecture
  - Definition of the digital twin/thread development methodology and alignment with the product development and support lifecycle
- The value that the definition of digital twin/thread brings to the A&D ecosystem
- Requirements for a defined, standards-based digital twin/thread interoperability model; this would include functional, data, and system interoperability standards
- Review and assessment of industry standards relative to the definition and use of digital twin/thread (Phase 4)

About A&D PLM Action Group

The Aerospace & Defense PLM Action Group (www.ad-pag.com) is an association of aerospace and defense companies within CIMdata's globally recognized PLM Community Program, which functions as a ***PLM advocacy group*** to:

- Set the direction for the aerospace & defense industry on PLM-related topics that matter to members (*including promoting, not duplicating, the work of standards bodies*)
- Promote common industry PLM processes and practices
- Define requirements for common interest PLM-related capabilities
- Communicate with a unified voice to PLM solution providers
- Sponsor collaborative PLM research on prioritized industry and technology topics

CIMdata administers Group operations, coordinates research, and manages the progression of policy formulation.

About CIMdata

CIMdata, an independent worldwide firm, provides strategic management consulting to maximize an enterprise's ability to design, deliver, and support innovative products and services by identifying and implementing appropriate digital initiatives. For nearly forty years, CIMdata has provided industrial organizations and providers of technologies and services with world-class knowledge, expertise, and best-practice methods on a broad set of product lifecycle management (PLM) solutions and the digital transformation they enable. CIMdata also offers research, subscription services, publications, and education through certificate programs and international conferences. To learn more, visit www.CIMdata.com or email info@CIMdata.com.

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Appendix A: Prominent Publications

During this research phase, the team identified the following prominent publications obtained through internet searches. These papers provide a baseline of digital twin/thread understanding and varying perspectives represented by leading industry organizations.

1. Title: Digital Twin models in industrial operations: State-of-the-art and future research directions. Link: https://www.researchgate.net/profile/Tsega-Melesse/publication/350281665_Digital_Twin_models_in_industrial_operations_State-of-the-art_and_future_research_directions/links/6058c81ba6fdccbfeafc7507/Digital-Twin-models-in-industrial-operations-State-of-the-art-and-future-research-directions.pdf
2. Title: 5 Ways to Cyber-Protect Your Digital Twin. Link: https://www.asme.org/topics-resources/content/five-ways-to-cyber-protect-your-digital-twin
3. Title: The Future of the Digital Twins Industry to 2025 in Manufacturing, Smart Cities, Automotive, Healthcare, and Transport. Link: https://www.prnewswire.com/news-releases/the-future-of-the-digital-twins-industry-to-2025-in-manufacturing-smart-cities-automotive-healthcare-and-transport-301028858.html
4. Title: Digital Thread Implementation in the Air Force: AFRL's Role. Link: https://www.nist.gov/system/files/documents/2017/04/19/boden_kobryn_usaf_nist_mbe_2016_dist_a.pdf
5. Title: Leveraging Digital Twin Technology in Model-Based Systems Engineering. Link: https://www.mdpi.com/2079-8954/7/1/7/htm
6. Title: Navy Platform Digital Twin. Link: http://onlinepubs.trb.org/onlinepubs/mb/2017Spring/fu.pdf
7. Title: NIST Advanced Manufacturing Series 400-2, Use Case Scenarios for Digital Twin Implementation Based on ISO 23247. Link: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=932269
8. Title: AIAA Digital Twin: Definition & Value. Link: https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/digital-twin-institute-position-paper-(December-2020).pdf

