Digital Twin & Digital Thread

Definition, Value & Relevance to Certification

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November 9th, 2021

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Digital Twin - Definition

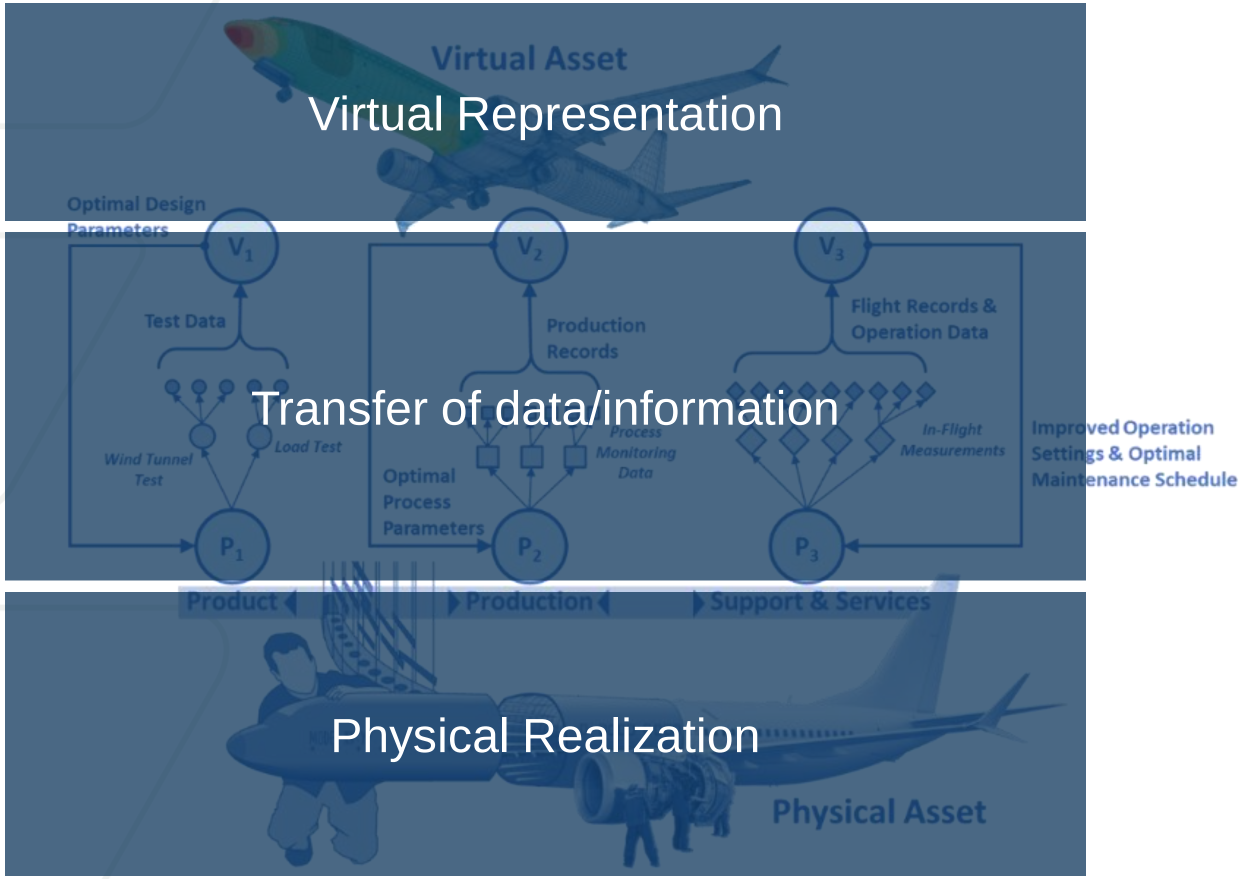
- Many competing definitions
- A Digital Twin is [1]….

	Attributes
… a set of **virtual information** constructs	Description
that mimics the **structure, context and behavior**	Content
of an **individual/unique physical asset**,	Association
is **dynamically updated** with data from its physical twin	Transience
throughout its life cycle,	Life Cycle
and **informs decisions**	Function
that **realize value**.	Benefit

Digital Twin - Definition

A Digital Twin is a virtual representation of a connected physical asset

- The "physical asset" can be a product, a process, an object, a system, a subsystem or combinations of those

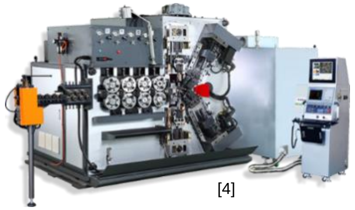


Example representation of the digital twin concept [1]


[8]


[3]


[2]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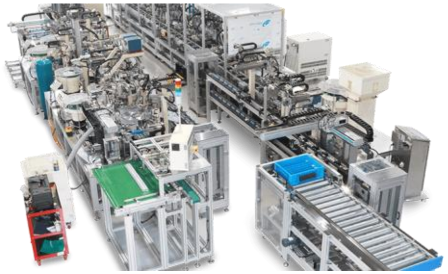
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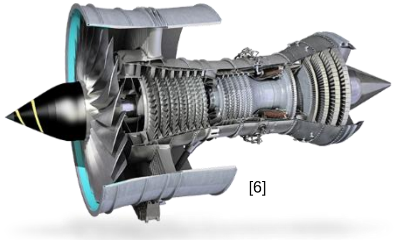
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The “Twin” Concept

- Dates back from NASA’s Apollo program [9, 10]
- Two identical space vehicles were built, the one remaining on Earth being called the *Twin*
  - Mirrors the conditions of the space vehicle during the mission [2]
  - Used extensively for training during flight preparations [2]
  - Used to simulate alternatives on the Earth-based model [2]

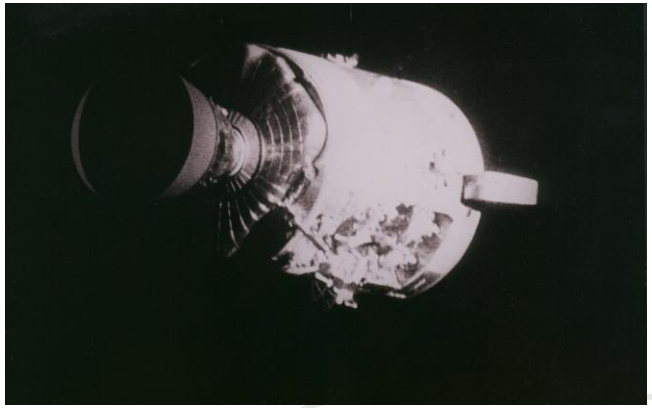
02 07 55 19	LMP	Okay, Houston - -
02 07 55 20	CDR	I believe we've had a problem here.
02 07 55 28	CC	This is Houston. Say again, please.
02 07 55 35	CDR	Houston, we've had a problem. We've had a MAIN B BUS UNDERVOLT.
02 07 55 42	CC	Roger. MAIN B UNDERVOLT.
02 07 55 58	CC	Okay, stand by, 13. We're looking at it.

NASA transcript of the communications with Apollo 13 at the time of the accident

Critical to the rescue of the Apollo 13’s crew by allowing engineers to test possible solutions from ground level [11]:

- “NASA mission controllers were able to rapidly adapt and modify the simulations to match conditions on the real-life crippled spacecraft, so that they could research, reject, and perfect the strategies required to bring the astronauts home.” [12]

Apollo Command Module Mission Simulator. Image credit: NASA



Damaged Apollo 13 Service Module. Image credit: NASA

Model vs. Digital Twin

- A **validated model** can provide a "snapshot of the behavior of an object **at a specific moment** [13]

vs.

- A **digital twin** provides an "accurate description of object that change **over time**" [13]

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Digital Twin Development – Important Considerations

- The proper definition & development of a Digital Twin require to
  - Identify the **intended users and use** of the Digital Twin.
  - Elicit and document the scope, context, points of view, environment, operational scenarios, major constraints, existing investments in tools and methods, and other key assumptions.
  - Identify Information and data ; **recognize data management and acquisition challenges.**
  - Identify modeling needs and capabilities:
    - ✓ Be aware of the **"agony of abundance"** when it comes to platforms, tools and languages
    - ✓ Understand the implications that modeling tools, languages and platforms has on **usability, scalability, extensibility or maintainability** of the models and Digital Twin
    - ✓ Other considerations: model fidelity, nature of the models and the availability of standards, services and APIs

Modeling Approaches to Digital Twins

Purely Physics-based

Models derived directly from the physics of the phenomena under consideration [13]
→ require a solid understanding of the physics, failure modes, degradation mechanisms, etc. considered

Advantages

- Particularly relevant when high level of accuracy are required (if data available to calibrate, verify model)
- Generalizes well to new problems with similar physics [14]
- Can be used to augment existing data
- Based on physics and reasoning [14] → explainability
- Errors/uncertainties can be bounded and estimated [14]

Limitations/drawbacks

- Sensitive and susceptible to numerical instability
- In some instances the physics of failure or degradation cannot be modeled
- The need to make simplifying assumptions due to a lack of available data or input severely impacts the fidelity of the models
- Building adequate, representative physics-based models of complex systems can be very time-consuming

Modeling Approaches to Digital Twins

Purely Data driven

- “Approach based on the assumption that since data is a manifestation of both known and unknown physics, by developing a data-driven model, one can account for the full physics.” [14]

Advantages
- Keep on improving as more data is available
- Fast to run
- Great for making predictions/inferences [14]

Limitations
- Supervised and unsupervised ML algorithms need large amounts of data
- Unbalanced or skewed data rarely results in reliable prediction models [2]
- Bias in data is reflected in model prediction [14]
- Lack of interpretability
- Only reliable within the region of input parameter space from which the data used to construct the model was taken [13]

Modeling Approaches to Digital Twins

Hybrid techniques

- Integration of both types of modeling approaches (e.g. integration of ML to physical processes)
- Have been demonstrated to give superior performance [14]
- e.g. Use of physics-informed ML

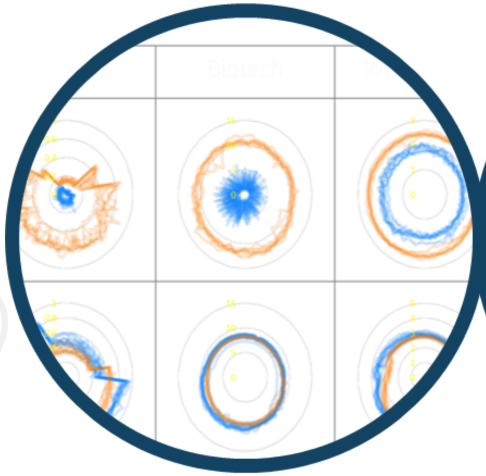
Selection of modeling approaches is dependent on:

- Availability of data to calibrate, verify and validate models
- Time frame the twin is to be updated [1] and decisions about the application need to be made
- What needs to be modeled: specific part vs. complete system [13]
- The needed or required generalizability and explainability of the models.
- Application/purpose of digital twin: driver for accuracy requirement

Digital Twin – Analytical Capabilities

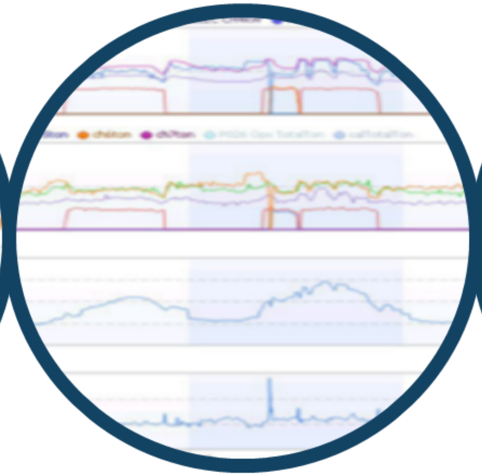
DIGITAL TWIN – ANALYTICAL CAPABILITIES

Descriptive



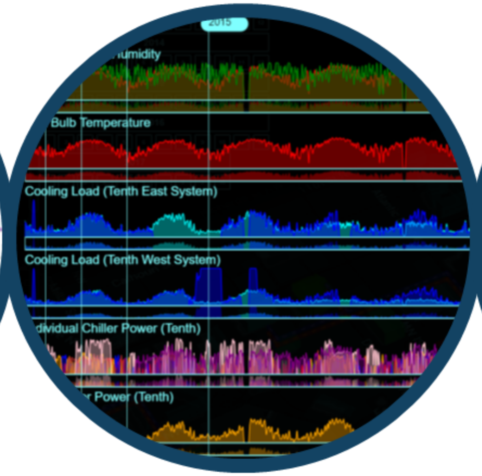
"What happened"
"What is happening?"

Diagnostics



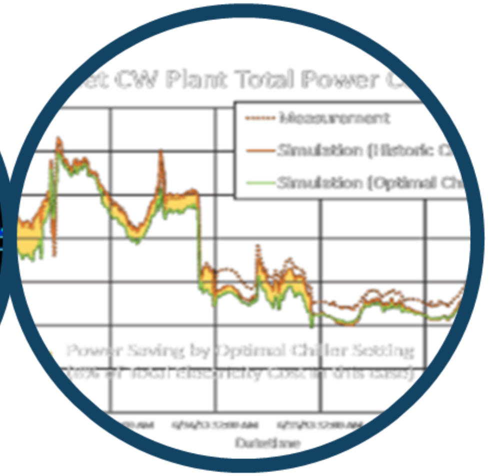
"Why did it happen?"

Predictive



"What is likely to happen?"

Prescriptive



"How to act in response?"

Digital Twin – Value

- Main purpose is to **create value**
- Dependent on the interests of the researcher or business involved. Can include [1, 15]:
  - Extracting **user preferences**
  - **Quantifying knowledge** about the state of the asset
  - Augmenting physical measurements and tests with modeling and simulation approaches to **reduce the cost and time associated with the certification process**
  - Conducting **virtual experiments** to enable **more informed lifecycle assessments and decisions**
  - **Enhancing operational performance and efficiency**
  - Providing **prognostics for sustainment and life extension**
  - Enabling **condition-based maintenance**
  - **Improving asset management**
  - Creating **knowledge for the next product**
  - Deliver **cost savings**

Digital Twin – Challenges to Development & Implementation

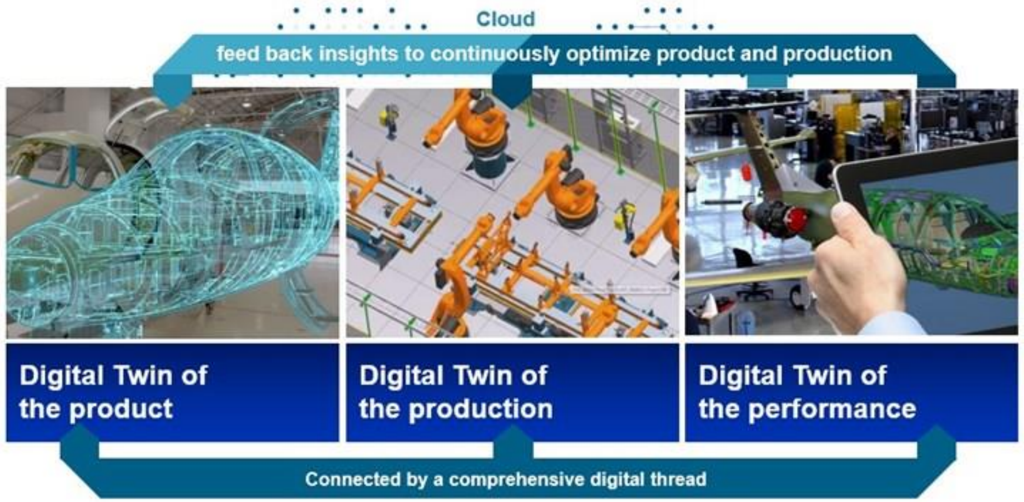
- **Tools and Methods**
- **Confidence & Trust**
- **Data/information integrity and authenticity**
- **Availability**
- **Maintainability**
- **Computing power**
- **Culture / Workforce**
- **Cybersecurity**

Digital Thread - Definitions

“Linkages of primary or **authoritative information** generated from all phases of the **product lifecycle** [19]."

“… an **enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative data**, information and knowledge to inform decision makers throughout a system’s life cycle by providing the capability to **access, integrate and transform disparate data into actionable information**" [18]

“The communication framework that allows a **connected data flow and integrated view of the asset’s data throughout its lifecycle** across traditionally siloed functional perspectives. [30]



Source | Siemens PLM [29]

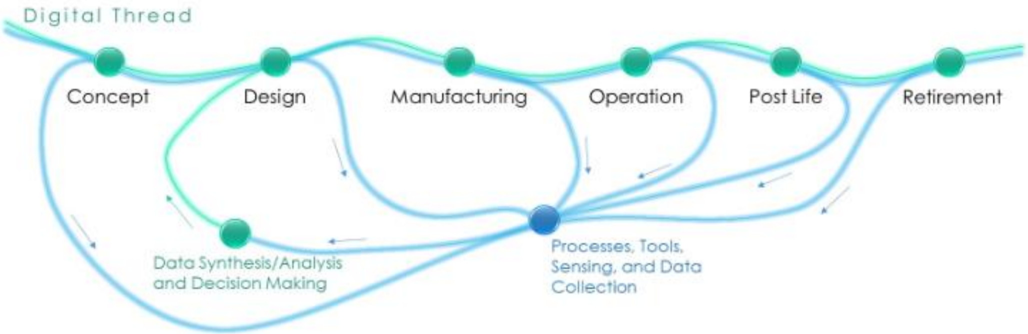


Illustration of engineering design with Digital Thread [17]

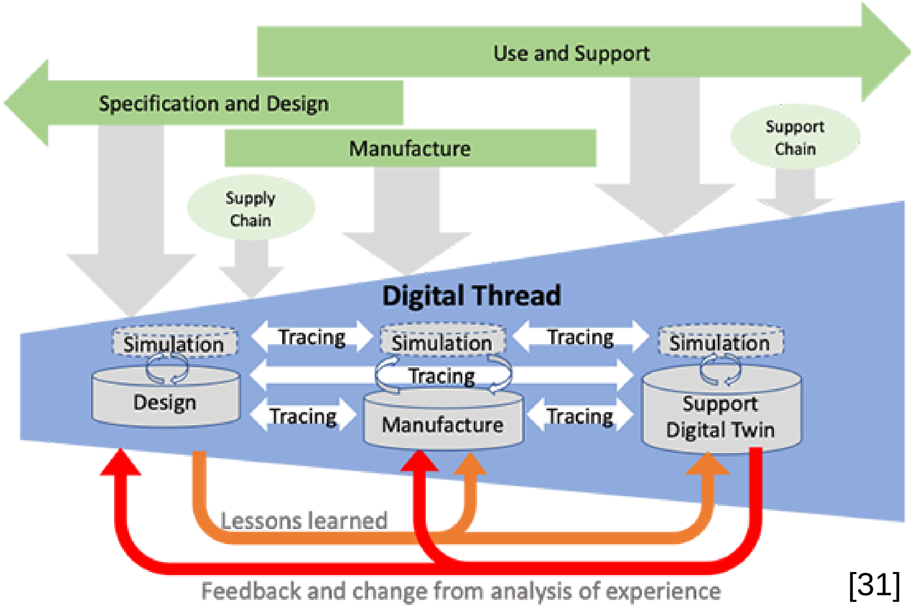
Additive Manufacturing Context & Relevance to Digital Thread

Additive Manufacturing is characterized by [16]:

- **Huge amounts of data being generated from multiple sources** on materials, process parameters, tests, and part qualification
  - → Opportunities for inconsistencies
  - → High volumes of data, often in a variety of formats, being distributed across stakeholders and projects
  - → Data being rarely aggregated or collated, resulting in missed opportunities to
    - Leverage collective knowledge
    - Reuse data/models
- Very specific data collection requirements
- The **complexity of the part design-process-material relationship and the effect of each on the part performance and reliability** → challenging path to certification by regulatory agencies
- Limited production lots → **prohibitive cost of physical testing**

Digital Thread - Benefits

- **Bi-directional Traceability:** Allows to trace [20]
  - The evidence and rationale that led to a decision, or
  - The provenance of data or requirements - and their maturation through the lifecycle
- **Consistency:** helps ensure that all authoritative derivative or successor information is fully compatible with its authoritative parent or predecessor information [20].
- **Increased Communication, collaboration across teams, stakeholders and customers:**
  - Consistency and integration lead to reduced workload of integrating product and lifecycle information across disciplines and teams [20].
  - The linking of all relevant meta-data
    - Enables the documentation of decision processes and outcomes
    - Makes available, in a transparent manner, the assumptions formulated throughout the design process → Facilitates the integration of latecomers, or stakeholders that may contribute at different levels of the analysis [21,22]



[31]

Digital Thread - Benefits

- **Workflow automation:** The integration capabilities of the digital thread provide the opportunity to partly or fully automate [20]:
  - The retrieval of authoritative information,
  - The translation, transformation, and fusion of that information for input into an analysis activity,
  - The collaborative execution of software that produces raw analysis data, and
  - Post-processing that visualizes or reduces the analysis data for consumption by analysts or downstream activities

- **Analytical capabilities:** The digital thread provides the foundational basis to many analytical capabilities critical to the ability to quantify risks and uncertainty and make informed decisions over the entire life cycle

- **Model Reuse:** The digital thread allows for the previous exploration of data, knowledge, and models to be available to all designers and decision-makers → Allows for the reuse of information in the development of both current and new design configurations [24].

Relevance of Digital Thread to Certification

Certification requires **full traceability of the data flow**, “from raw material testing through part design, material characterization, manufacturing, post-processing, physical testing, and simulation” [16].

In the context of AM, the Digital Thread

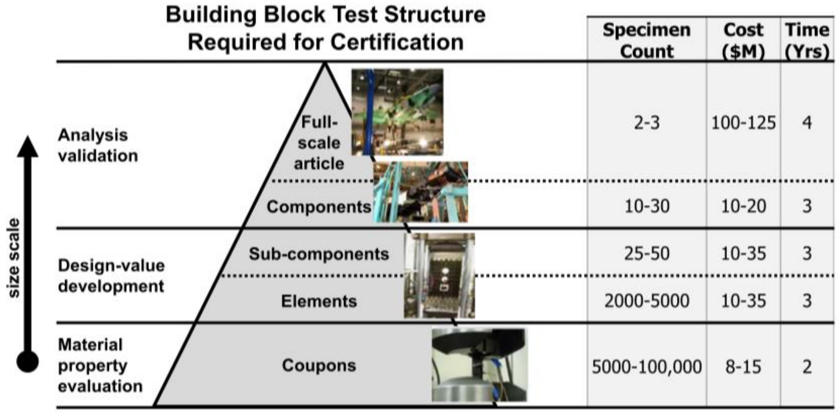
- Provides a repository to organize, manage, mine, search/discover the data generated from research to full production
- Maintains the complex relationship between the material, part geometry, individual processes, as well as the subsequent physical and virtual testing

→ Understanding and **quantifying the impact of specific inputs and variables on material behavior as well as part quality and performance**

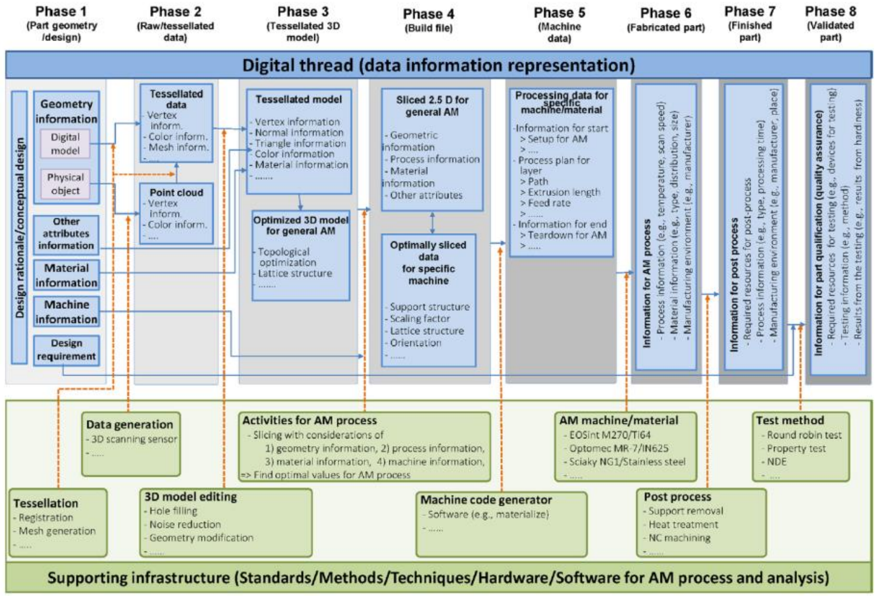
→ Establishing **correlations and relationships among parameters that experimental studies cannot easily couple/identify** [26]

→ Predicting performance and validating those results against physical test results

→ Quantifying and reducing uncertainties



Building block test structure for certification [25]



A diagram of an end-to-end digital thread and its phases and transitions [27]

Relevant Resources & Events

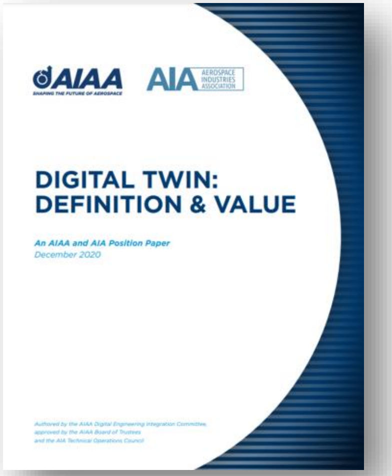
Digital Twin: Definition & Value - An AIAA and AIA Position Paper

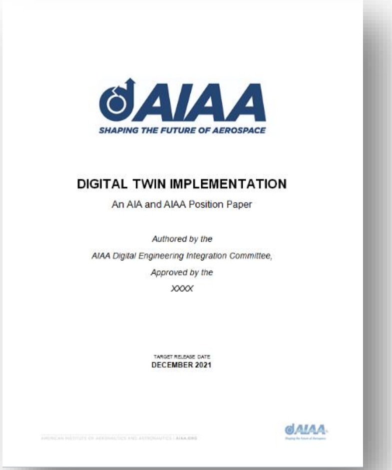
- https://www.aia-aerospace.org/report/digital-twin-paper/
- https://www.aiaa.org/advocacy/Policy-Papers/Institute-Position-Papers

Digital Twin Implementation Paper: Leveraging Digital Twin position paper context and recommendations to promote implementation and use of digital twins for value realization across the Aerospace Industry – Expected Release: Spring 2022

Digital Thread: Definition & Value - An AIAA and AIA Position Paper: Expected Release: 2022

Virtual Technical Panel on Digital Engineering for Product Qualification and Certification (AIAA SciTech Forum – January 3rd, 2022 @ 11:30am PST)





Thank you

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