DIGITAL TWIN: DEFINITION & VALUE

An AIAA and AIA Position Paper
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Authored by the AIAA Digital Engineering Integration Committee,
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Statement of Attribution

This paper was drafted over the spring of 2020, reviewed in the summer of 2020, approved by the AIAA Board of Trustees in October 2020, and approved by the AIA Technical Operations Council in December 2020. The AIAA Digital Engineering Integration Committee consisted of members from academia, industry, and government who, collectively, have a breadth of experience in the concept of Digital Twin.

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Executive Summary

The rapidly increasing complexity of aerospace systems has significantly outpaced conventional development techniques [1]. As a result of the increased complexity of such systems, the costs associated with traditional aerospace activities, such as physical prototyping, physical testing, and proximity/periodic maintenance will continue to increase. Virtual capabilities that can simulate physical environments with increasing levels of fidelity, speed and granularity hold the promise to decrease these costs [2-4]. One such virtual capability is that of the concept of Digital Twin, for which a short-form definition is provided in Table 1 and a representation is given in Figure 1.

Table 1: Digital Twin Definition

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

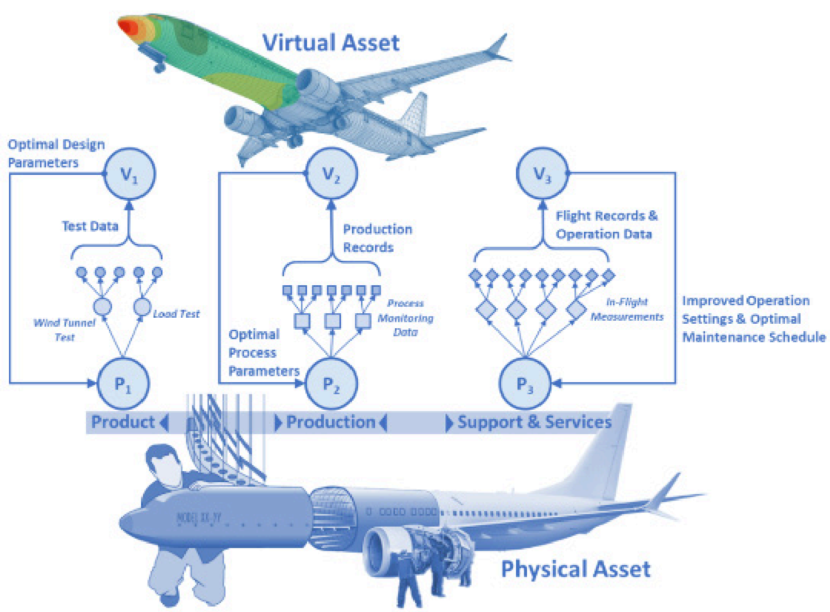

Figure 1: Representation of the Digital Twin Concept

A Digital Twin is a virtual representation of a connected physical asset and encompasses its **entire product lifecycle**. Its value stems from the ability to shift work from a physical environment into a virtual or digital environment and from the capability to predict asset conditions in the future, or when physically not desirable, by leveraging the digital model. This in turns leads to significant decreases in the resources needed to design, produce, and keep aerospace assets operational. The objective of this paper, which has been developed by members from academia, industry, and government, is four-fold: 1) provide the Aerospace community with a common definition of the Digital Twin, 2) illustrate Digital Twin capabilities through a number of applications and value examples, 3) discuss the alignment between the Department of Defense (DoD) Digital Engineering Strategy and aerospace industry's viewpoint of the Digital Twin, and 4) identify future focus areas and activities for accelerating value realization from the use of Digital Twins. In particular, this paper recommends establishing a Digital Twin "Center of Excellence" for collaboration between Academia, Industry, the United States Government, and relevant Certification Authorities to tackle the business, technical and cultural needs, gaps, and challenges identified by the authors.

Purpose

The purpose of this paper is to provide an aerospace industry (including civil, military, and commercial) perspectives on the Digital Twin and the significant benefits and rationale to accelerate embracing the fourth industrial revolution referred to as digital transformation. The digital transformation, which is driving model-based technological advances that are aggregated within the Digital Twin, is expected to greatly accelerate the pace from research to the deployment of advanced systems and enable the aerospace industry to successfully compete in the global market with innovation of products and services, customer experience and overall lower total lifecycle cost.

This position paper represents a single coherent consensus of opinions across multiple organizations within the aerospace industry. The organizations represented by contributors to this paper, AIAA, and AIA, agree there are additional viewpoints and perspectives beyond the well-written DoD Digital Engineering Strategy [5] that facilitate a more comprehensive and holistic understanding of the benefits through a successful digital transformation. Although the DoD Digital Engineering Strategy was originally developed for application to military programs, the underlying strategy is fully applicable to civil and commercial aerospace industries as well.

In this position paper, the definition of a Digital Twin will be clearly articulated with potential applications and benefits for the entire aerospace industry. Multiple Digital Twin Applications will be discussed with Value mappings from aerospace industry and academia perspectives to illustrate how Digital Twins help improve performance, affordability and reliability and increase organizational efficiency.

Digital Twin Definition

A Digital Twin is defined as

> *A set of **virtual information** constructs that mimics the **structure, context and behavior** of an **individual / unique physical asset**, or a group of physical assets, is **dynamically updated** with data from its physical twin **throughout its life cycle** and **informs decisions** that **realize value**.*

This definition, which best represents the position of members of the Aerospace Industry, originates from an extensive and thorough review of the literature on the subject. During this review process, a data-driven approach was followed to identify the keywords that are most commonly used when characterizing the Digital Twin. Following this approach, the aforementioned long-form definition was formulated and voted on by members of the aerospace industry.

The ***essential elements*** of a Digital Twin are a virtual representation (model), a physical realization (asset), and a transfer of data / information (connected) between the two. Hence to have a **Digital Twin requires a physical asset**.

A Digital Twin encompasses the **entire product lifecycle of a physical asset**, i.e. the design and engineering phase ("As Designed"), the manufacturing phase ("As Built"), and the operational/sustainment phase ("As Used" and "As Maintained"), whenever a physical asset is employed. In doing so, it enables better information connectivity and knowledge continuity [6, 7], which eventually leads to improved effectiveness and efficiency and better design and manufacturing through the continuous refinement of designs and calibration of models [8, 9]. As such, models, as well data from both the models and the physical asset, are critical elements of the Digital Twin. Models ensure that the asset is properly represented while providing a medium for the analysis, simulation, and optimization of phenomena of interest [10] across the life cycle of the product. These models can be purely data-driven, purely physics-/simulation-driven or a hybrid of the two [11]. Data is exchanged across models as well as collected in real time from the physical asset by means of improvements in communication standards and protocols together with cloud-based platforms. This data can then be used for descriptive, diagnostic, predictive and/or prescriptive analytics to inform decision making at every lifecycle phase.

As mentioned, Digital Twins encompass every stage in the lifecycle of a system whenever a physical asset is employed. A Digital Twin of a material coupon can combine multi-level physics models of the material with physical experiments and machine learning approaches to develop a value-added, comprehensive, virtual representation of the material. This includes the characterization of the type of uncertainty, which can be due to imperfect knowledge (epistemic uncertainty) or due to inherent, irreducible chance (aleatory uncertainty). Digital Twins of components and subsystems can be developed in concert with physical prototypes to increase valuable knowledge about their performance, reducing the number of physical prototypes required and helping to improve future designs. Digital Twins of mechanical and electronic components can also be implemented in hardware-in-the-loop or software-in-the-loop facilities. Digital Twins of systems can be implemented in simulators integrated into live-virtual-constructive exercises to increase the mission value of the asset of interest. Digital Twins of manufacturing processes can be used to optimize the quality and economy of a part or factory either through conventional or additive manufacturing assets. Digital Twins of a flight test vehicle, including the characteristics of the individual test pilot, can be employed to optimize flight test points to produce the most knowledge per flight.

A Digital Twin applied to an individual final asset creates the maximum business value by quantifying knowledge about the state of the asset, enhancing operational performance (including autonomous control), providing prognostics for sustainment and life extension, extracting user preferences, and, creating knowledge for the next product and enabling feedback during early trade analyses. In addition, the Digital Twin can be used to (i) augment physical measurements and tests with modeling and simulation approaches, as a means to reduce the cost and time associated with the certification process and (ii) enable more informed lifecycle assessments, as a component or system moves from the as-designed, as-built, as-tested stages into service. Consequently, the Digital Twin for the final product should not be an add-on feature but should be an integral part of the initial concept, design, and development of the system using a progression of physical assets from the component to the system. The value expected to be extracted through the use of a Digital Twin, the sensors and data required to create the value, and the testing and validation of the Digital Twin to produce the end value should be a requirement for the development of the system.

To keep the definition of a Digital Twin as straightforward as possible it should be defined in terms of the ***essential elements*** – a model, physical asset, and connected knowledge transfer employed to increase value. Additional attributes of a Digital Twin at various phases in the lifecycle should be attributed to the nature of the physical asset, e.g., coupon, component, subsystem, system, flight test, manufacturing process, end-product. Figure 1 provides a notional representation of a Digital Twin.

In an effort to provide a shorter definition that everyone can support and clearly articulate, the following short-form definition is provided:

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

Digital Twin Capabilities

While the capabilities enabled by the Digital Twin are vast, the discussion is organized into two categories for brevity: (i) use of modeling and simulation to reduce the time and cost of the certification of components and sub-systems, and (ii) use of information acquired throughout the product lifecycle to make more informed decisions about the current and future status of a component and subsystem and provide feedback to the institutional design practices and knowledge base for future engineering efforts.

Recent advancements in modeling and simulation tools virtualize aircraft development and reduce the cost and span of aircraft development. A suite of software tools is available to aid in the transformation of the engineering paradigm to a virtual medium, including design, manufacturing, materials evolution and capabilities, aerodynamics, structural integrity, and performance analyses. More importantly, these tools can be integrated to account for the interconnectivity of the engineering lifecycle, and expedite the iterative design, analysis, and testing feedback loops which have historically been necessary. By moving much of the analysis to a virtual medium, the number of costly physical tests and iterative re-design cycle loops can be reduced, thus resulting in a reduced time and cost for the certification process. Data from physical tests (e.g. coupon tests, wind tunnel tests, ground tests, flight tests, operational tests, etc.) are also used to update assumptions made to construct virtual tests. The Digital Twin does not eliminate the need for physical measurements and testing, but only reduces the number and dependency on this form of information. The physical and virtual information can be fused to provide a more robust and broader dataset, which further enables the use of machine learning and data science approaches for decision making.

While many decisions are made throughout the product lifecycle, traditionally these decisions are informed by experience about the variables that influence the ultimate performance of the physical asset [3]. The uncertainties in the current status or the external variables affecting the physical asset result in propagating uncertainties into its current or future performance. The Digital Twin harnesses information collected throughout the lifecycle to update and better inform the analysis and decision-making process of the physical asset. This information takes on many forms, which includes, but is not limited to performance data, as-manufactured geometries, material's microstructure and pedigree information, in service loading spectrums, component damage and degradation. With the advent of novel sensor technologies, the capabilities and fidelity of this data/information will grow exponentially. Further, the improved state, material, and structural health monitoring and awareness technologies that are being developed can inform decisions on maintenance, repair, and the overhaul of individual products or entire fleets. Finally, by capturing the data throughout the product lifecycle and making it readily available to designers, the next version of a feature, part, or sub-system can be improved based on the lessons learned from data collected on previous versions.

Digital Twin Applications & Value Examples

Table 2.1: Product Digital Twin Applications

Product Digital Twin ("As Designed")		
Digital Twin Type	**Example Applications**	**Value**
Digital Twin Calibration	Validation/Calibration of Digital Twins based on real-world product operational data/conditions (e.g. coupon tests, wind tunnel tests, ground tests, flight tests, operational tests). Digital Twin Calibration Examples: 1) **Ops Analysis** - Models to develop mission planning survivability, and tactics. 2) **Structural** - Finite Element Model (FEM) for Loads and Life management. 3) **Variation** - Reflecting tolerances and variation in parts and tooling to identify statistical fit issues ahead of first article. 4) **Vehicle Systems** - Modeling and simulation of product systems/subsystems. 5) **Flight Controls** - Modeling and simulation of vehicle flight controls. 6) **Mission Systems** - Modeling and simulation of mission systems/software. 7) **Signature** - Model that captures initial design and repairs that impact Radar Cross Section (RCS). 8) **Sustainment** - Modeling and simulation of product sustainment.	Improves product design and first time quality through more accurate and higher fidelity Design Models & Analytical Methods. Enables accelerated decision making based on a validated authoritative source of truth. 1) Ensures that the product design is optimized to achieve mission performance objectives. 2) Validates structural loads and product structural life projections. 3) Used with metrology measurements to identify and prevent part variation that can cause impacts to early article manufacturing. 4) Validates the design and performance of product systems to reduce lab/flight testing. 5) Enables control law development to optimize flight dynamics and support pilot training. 6) Validates the design and performance of mission systems to reduce lab/flight testing. 7) Validates product survivability and operational mission performance. 8) Validates product maintenance/sustainment approach, basing requirements, & equipment.
Performance monitoring, validation and optimization	Virtually validate product performance while also showing how products are currently acting in the physical world to optimize performance. Embedding Serial Number adapted closed-loop controls for operational and environmental factors to operate closer to performance boundaries.	Lower system cost for target performance (avoid design margin from over-engineering and/or reduce requirements for materials/physical performance via in-product adaptive controls) – e.g., active load reduction on wind turbines through angle of attack adjustment [12].
Design optimization and upgrade analysis	Analyze product performance under various conditions and make adjustments in the virtual world to ensure that the next physical product will perform exactly as planned in the field.	10-75% reduction in cycle time [8] improves quality of the final manufactured product and enables faster iterations in response to customer feedback. Enables product version evaluation to determine which features provide the optimal solution. Data analytics can facilitate timely analysis of significant volumes of data generated to provide insights into potential new products and revenue streams. Reduce iteration through early discovery of downstream stakeholder conflicts (e.g. fewer Maintenance Review Boards for non-conforming parts, sole-source (specialized) supplier costing, and materials availability/cost) [9].
Market Gap Analysis & Capabilities	1) Analysis of Alternatives for capability/need assessment. 2) Reducing time to develop & certify through high fidelity analysis from a Digital Twin.	1) Reference [13] 2) Reference [12]

Table 2.2: Production Digital Twin Applications

Production Digital Twins ("As Built")		
Digital Twin Type	**Example Applications**	**Value**
As-Built Configuration	Details of the aircraft as-built configuration that are not associated with the engineering configuration such as serial numbers, cage codes, sustainment data loads, measurements during build, nonconformance documentation, supplier disclosures, and added inspections.	As-Built configuration contains nonconformance information, repairs, post-delivery article inspection requirements, supplier disclosure notifications, and factory test data required for aircraft or sustainment data loads. Value is to provide the customer a complete record of the as-built configuration and highlight where the configuration may differ from the engineering configuration to support sustainment maintenance and modifications. This assumes mainly automated data collection and accumulation.
Performance validation and optimization	Model of aircraft production performance including task span times, hours per unit, sequence of operations.	Twin provides descriptive and predictive insight into factory performance (cost, quality, schedule) to support learning curve estimates, staffing and tooling requirements, and trends to identify opportunities for continuous improvement.
Factory Simulation	Discrete event and digital physical modeling to simulate physical factory layout, materials flow, tooling, and identify bottlenecks and the results of disruptions to the factory operations such as quality or parts problems.	Factory physical and statistical models simulate factory operations to validate product fit and flow along with identifying bottlenecks and helping to identify requirements (staffing, tooling, and support staff) as factories expand to rate production. Twin value is to accurately predict requirements for the factory and enable stable production even as rates rise and disruptions impact the factory. Dynamic scheduling to identify critical path impacts and mitigation strategies.
Material Modeling Twins As-Built Part/Component Twins for Quality	Models/simulations of the material structure (e.g. grain structure, or precipitates) which include sizes and distributions. Part/Component level models/simulations which include nonconformances and deviations from original engineering releases.	Reported example of potential of 50% percent reduction in material development time, up to 8x reduction in testing, improvement in component capability by integrating material modeling/simulation with design optimization efforts. Reduction in material certification time by up to 25 percent (3-4 years) [14, 15]. Supports functional based dispositioning of components/parts from 'as-built' reality for Quality decisions in Material Review Board (MRB) efforts [16].

Table 2.3: Support & Services Digital Twin Applications

Support & Services Digital Twins ("As Used" and "As Maintained")		
Digital Twin Type	**Example Applications**	**Value**
Performance monitoring	Cross-fleet asset-to-asset operator-to-operator performance normalization to environmental and multi-granular operational baselines.	Improve forecasting and just-in-time inventory planning, predict and control impact of performance drift, product variation and use context. Reduce time to identify and correct sub-performing units (e.g., turbines across a wind farm) and optimize for KPIs (e.g., annual energy production/AEP). SN and PN model calibration and convergence through continual learning, leading to robust, reliable asset performance forecasting relative to contextual degradation.
Fleet Enterprise Twin	Product level (SN specific) models/simulations which include 'as-operated' data (e.g. Equipment Health Monitoring, and Environmental context data) to inform maintenance decisions & feedback to operator to improve performance.	Modeling/simulation of asset to assess current operating context; provide recommendations to minimize fuel burn, signal when asset needs maintenance; enables learning from its operations and other engines in the fleet.[17] GE Trip Optimizer 10% fuel reduction [18, 19].
Heath status validation and optimization	Failure Prediction and Predictive Maintenance: incipient failure detection to adapt operation to life-extending mode so failure does not precede service. Predictive part needs for long-lead manufacture or distribution logistics.	Mitigation of catastrophic failures through graceful degradation. Reduced downtime waiting on part availability. Improved specificity of maintenance workscoping for condition-based maintenance. Improved control and performance toward condition-based operation. Challenges: sensor diagnostics (higher accuracy/lower lead time) getting adequate lead time to act from time of detection, predictive algorithms (lower accuracy/longer lead times) ability to catch sensor-elusive failure modes (e.g., cracks).
Failure analysis	Root Cause Analysis (RCA) based on part/component specific full-genealogy (as-designed, as-manufactured, as-operated, as-serviced) and detailed operational use data. New failure modes (unknown unknowns) identified in operational data via unsupervised manifold learning for anomaly detection.	Reduced downtime diagnosing ambiguous cause, learnable scope of impact across fleet to adjust preventative maintenance schedules for peer assets, recalibrations for condition-based maintenance. Improved re-designs building on learned field performance vs. as-designed for baseline design.
Condition-based maintenance	Feedback from sensors enable condition-based maintenance; fatigue life analysis and severe event tracking. Risk-based workscoping based on predicted life vs. service duration and interval to next service e.g. tailored maintenance actions by individualized predicted part life and operational projection to next maintenance event.	Improves product reliability and availability and lowers maintenance costs. GE Digital [8] saw a 6% increase in product reliability, 40% reduction in maintenance costs and $11M in cost avoidance by using Digital Twins to detect and prevent 3 failures. Improved service-ready inventory of replacement parts to provide a "full kit" at maintenance. Reduction of unplanned downtime, extraneous waste and cost from premature part replacement, greater duty cycle for operation, improve just-in-time maintenance reliability [20].
End-of-life decision aid	Part/component level model evaluating as-used vs. as-designed vs. as-repair(able).	Advise decision to re-use, recondition, recycle or scrap, based on historical operational environment. Reduce scrap, service costs, remanufacturing costs, and downtime. Challenge: predictive accuracy beyond operation and environment factors – due to multi-granular twin variability (part to part vs. engine to engine).

As-Used Part/Component Twins for Improved Material Management	Part/component level models/simulations (serial number specific) which include geometric & material deterioration and deviations from original engineering releases & as-built conditions.	Supports functional based dispositioning of components/parts from 'as-used' reality for material management decisions in MRO efforts. Account of deteriorated condition with Prognostic Health Monitoring for improved life calculation/remaining useful life predictions. [14, 16] Data can additionally provide calibration feedback to product Digital Twins and design models to improve predictive accuracy and/or annotations.
Operational Trade-off	Scenario analysis to evaluate trade-off impact of operational choices.	Enable end-user discretion to generate value through intentional prioritization of performance vs. endurance based on mission or market conditions, while tracking impact on contractual service pricing / costs. e.g., profitable demand surge vs. extending time to maintenance outage (trade life for performance – or vice versa - when economically justified).
Data Integrity Sentinel	Anomaly detection in measured data, control instructions, system metadata (e.g., latencies) vs. learned baseline and physics-based model to identify faults or malicious activity and protect asset and operational integrity.	Resilience through isolation of impact from defects, tampering, and/or reliance on network connectivity by enabling localized control modes minimizing degradation of operations and safely alerting system-wide monitors with diagnostic evidence [21].

Tables 2.1-2.3 are not meant to be exhaustive, but only to provide representative examples of Digital Twin types, applications and projected value. For example Digital Twins could also be used for training applications (e.g. connecting appropriate FAA-approved simulation systems into an airplane Digital Twin to predict pilot performance under different operational scenarios). Other potential Digital Twin applications include reliability/availability/maintainability/safety prediction, accident reconstruction and inventory prediction/estimation. All of these potential applications should be explored further.

Alignment to Aerospace Industry

Although the DoD Digital Engineering Strategy was originally developed for application to military programs, the underlying strategy is fully applicable to civil and commercial aerospace industries as well. Indeed, non-DoD organizations are fully engulfed in the fourth industrial revolution. Beyond DoD benefits, there are corporate benefits. The primary benefit is the ability to move late lifecycle changes earlier in the lifecycle where electrons are cheaper than atoms (i.e. software vs. hardware fixes). DoD and commercial business alike benefit from reduced late lifecycle modifications. This requires substantially more modeling and especially trust in the models developed. As mentioned in the great quote by George E.P. Box [22] "…all models are wrong; the practical question is how wrong do they have to be to not be useful." So, how much do you trust your model acknowledging that it is not perfect? The fourth industrial revolution emphasizes the shift from using models to confirm years of experience to now trusting models to make decisions. So, why cannot years of experience suffice anymore? Systems are becoming increasingly interdependent where one system will not only influence another system but will alter its behavior causing unanticipated emergent behavior (then that system alters another system causing a cascade effect). Experience is limited because no one person, or even group of people, can know everything. It simply is not practical to get every knowledgeable person in a room for very large interdependent systems and predict every combination of scenarios (both nominal and off-nominal). The ability to make decisions faster to develop products that quickly adapt to external changes allows for the increased likelihood of product validation. This is important to both the DoD and commercial business as it helps ensure market and/or battlespace dominance.

Recommendations and Next Step

This document has presented a unified Aerospace Industry position on the definition and value of Digital Twins. This work is intended to provide a baseline position and understanding for facilitating the required collaboration efforts across Industry, Academia and Government. Broader enterprise benefit realization from identified Digital Twin applications will require a collaborative pursuit of the following focus areas and activities for accelerating value realization from the use of Digital Twins.

1. Business & Transactional (e.g. what & how does Industry "deliver" to Customers?)

The value of a Digital Twin is still not clearly understood or articulated in a way that enables and incentivizes definition of 'win-win' business models and contracting best practice across Industry (multi-tier) and Government.

- **Economic Impact**: Need a review of the economic considerations and impact of Digital Twin approaches that can inform better decisions across product development, production and sustainment while ensuring economic health and wellbeing of the Aerospace Industrial Base. In particular, there is a need to trade the upfront cost of developing and maintaining Digital Twins against their expected economic impact/return on investment.
- **Intellectual Property & Cybersecurity Strategy**: Furthermore, to enable use of data with Digital Twins for cross life cycle and cross supply chain value realization, these new approaches will require alignment of strategies for how to manage Intellectual Property, its protection (e.g. data ownership & access rights), and cybersecurity (e.g. latent malware detection).
- **Contractual Language**: Finally, with improved understanding and alignment to views of value, economic impact and IP considerations, it is necessary to revisit contract language to establish appropriate terms, conditions and incentives for accelerating value realization from Digital Twin capability.

Significant work is underway across a number of Government and Professional organizations in this space, but often as siloed and uncoordinated efforts within their respective view of the system.

2. Technical & Analytical (e.g. what are best practices, lessons learned, and technical investment needs to accelerate value realization?)

Although there has been substantial progress in application of Digital Twin capability for realizing benefit by some Aerospace Industry members, the broader adoption and use of Digital Twins is limited by several technical & analytical challenges.

- **Standards**: Need to develop appropriate standards and/or standard approaches so that Digital Twins can interact with other Digital Twins across the life cycle and supply chain. Many existing Professional Societies are pursuing standardization efforts across Industry sectors, but there is limited coordination and awareness across efforts. In many of the best examples of Digital Twin application, the majority of these commercial sector implementations are proprietary. Significant value and increased collaboration could be realized by establishing appropriate foundational open standards (e.g. data and models) and life cycle architecture frameworks. Therefore, additional focus and effort should also be given to addressing which elements of this foundation should be open.
- **Toolsets & Methods**: To advance the quality and practice of Digital Twin use across the broader Aerospace community, further development and improvement in tools and methods are required including, but not limited to, multi-physics modeling, probabilistic framework development, artificial intelligence and machine learning advances in configuration management to offload manual burden and increase connectivity, verification/validation/accreditation, certification and uncertainty quantification of Digital Twins. Furthermore, a common

catalogue of trusted/preferred engineering tools and best practice methods are needed for accelerating community understanding, adoption and use.

- **Data Curation**: Acknowledging security, export and IP sensitivity of Digital Twin models, there is a need to identify industry accepted solutions for how and where Digital Twins are stored and maintained along with the associated long-term archival and retrieval (LOTAR) approaches required by Certification and Airworthiness authorities. Furthermore, in addition to storage and maintenance of models and simulation, access to and curation of 'twin data' like field performance, reliability and failure data is important as a Digital Twin does not exist without a connected physical asset.
- **Infrastructure**: Though large Industry and Government collaborators have built out substantial Information Technology platforms to support internal realization of Digital Twin and Digital Enterprise capability, small and medium size players across the Aerospace Industry often have not. This is further underscored by emerging Cyber Security (e.g. malicious data) threats and associated requirements. This requires definition of appropriate requirements for an Integrated Digital Environment (IDE) that enables real-time access to authoritative source of truth data for customer/supplier collaboration while protecting IP, enabling backward compatibility, and protecting against malicious data corruption across multiple tiers of the supply chain.

Again, though many Professional Societies and Government efforts exist to address elements of the above challenges, an Aerospace Industry forum does not yet exist for facilitating a robust and transparent discussion between Industry and Government for Digital Twin benefit realization across the Enterprise.

3. Cultural (e.g. how does Industry achieve mindset change for full value realization?)

Cultural inertia is common in the early implementation of novel concepts. While the concept of Digital Twins has received mainstream acceptance, it has not yet realized its full value due to the following cultural challenges:

- **Terminology**: Though this paper has established a unified definition of the Digital Twin, many organizations still have bespoke views of the Digital Twin relationship to the broader Digital Enterprise. To support cross Aerospace Industry alignment and communication, there is a need to establish a common taxonomy of parts (e.g., objects like 'hand,' 'wheel,' 'taillight'), an ontology of concepts for each of those parts (e.g., 'rotate,' 'stall,' 'level flight attitude'), and naming US English as the linguistic form for all information and associated data. The data is either numbers (i.e., measures) or words (i.e., semantics). For each digital twin, there is an associated, and constrained, semantic vocabulary, for each aircraft type. The language or 'Rosetta Stone' of terms, definitions, taxonomies, and ontologies for the Digital Twin must be standardized to assure universal understanding and interoperability. This enables design for interoperability and avoids vendors creating proprietary twins that are not interoperable (i.e., words or expressions do not match, or are left to assumption).
- **Workforce Development**: Formalize, nurture, and grow critical skillsets through appropriate training & education of the work force. The development of Digital Twins requires skills at the intersection of many disciplines, including but not limited to: systems engineering, systems thinking and architecting, data analytics, machine learning/artificial intelligence, statistics/probabilistic, modeling and simulation, uncertainty quantification, and decision science. These disciplines are rarely taught within the same academic curriculum. To keep tomorrow's workforce current and relevant, new multidisciplinary programs, informed by industry and governmental organizations' needs and insights, should be proposed that are encompassing of the aforementioned disciplines.
- **Certification by Analysis**: Though the benefit opportunity for increased use of modeling and simulation to accelerate both design and manufacturing type certifications/qualifications are great, the current Regulatory requirements, policies and landscape do not allow for full realization of this benefit. Collaboration across Industry and Airworthiness authorities is still needed to appropriately transition from classical "design-build-test" to "model-analyze-build" approaches to accelerate product and process Certification/Qualification. In this context testing will not be removed entirely. Rather, more targeted physical testing will be done to: 1) verify, validate, calibrate and/or quantify the uncertainty of models and simulations, or 2) close a knowledge gap.

AIAA is working a 'Certification by Analysis' recommended practices paper which provides further context as to the opportunities, challenges, and guidance in this area.

In light of the above challenges, gaps and needs, the Aerospace Industry recommends establishing a Digital Twin "Center of Excellence" for collaboration between Academia, Industry, Government and relevant Certification Authorities to:

- Articulate and align on definition of the Digital Twin value,
- Champion efforts to address and close the identified business, technical and cultural gaps above,
- Provide guidance for Government Procurement Policy and investment based on a common view of value and gap assessment,
- Serve as a trusted authority to establish and share lessons learned, best practices and standardization,
- Serve as a trusted authority for establishing verification, validation, accreditation and 'Maturity Level' of Digital Twins for quality process management of the readiness for application,
- Act as advocate for workforce development and educational curriculum, and
- Enable collaboration between Industry and Airworthiness for appropriate adoption of Digital Twin capability in Certification by Analysis efforts.

Initial formulation of an appropriate Aerospace Industry Digital Twin Center of Excellence collaboration should leverage feedback and expertise from existing Academia, Industry and Government championed efforts including:

- AIAA Digital Engineering Integration Committee (DEIC)
- AIAA Certification by Analysis (CbA) Community of Interest
- AIA Business Technology Interoperability Committee (BTIC)
- United States Office of the Secretary of Defense (OSD) sponsored Digital Engineering Working Group (DEWG)
- United States Air Force Digital Engineering Enterprise Office (DEEO)
- International Council on Systems Engineering (INCOSE)
- Object Management Group (OMG) Digital Twin Consortium

In addition, efforts should proceed with purposeful awareness and engagement across other Professional Societies to ensure best practice is leveraged across other societies where appropriate. The above noted professional societies and Government programs are already partially leveraging Digital Twin capability for islands of benefit, but not in a way that exploits a broader Industrial Base collaboration. In addition, supplementary position papers describing the digital thread, digital ecosystem, and digital systems model need to be developed. Further, collaborative case studies for these digital engineering topics should be explored. Indeed, collaborative case studies investigating the Digital Twin phenomena are next steps following this paper. Now is the time to accelerate the Aerospace Industry benefits from this transformative capability... together.

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Annex A: DoD Digital Engineering Strategy Alignment

The DoD has a specific interest in National Security through very large interconnected systems. Figure 2 illustrates the five goals of the DoD Digital Engineering Strategy along with the similarities that exist with the industry Digital Twin. For example, the first goal of the DoD Digital Engineering Strategy is to "Formalize the Development, Integration, and Use of Models to Inform Enterprise and Program Decision Making" as represented in the purple top rectangle in Figure 2. The corresponding Digital Twin tenet aligned to this goal is shown in the top right purple rectangle. There is a similar symmetry across the remaining four tenets (i.e. 2-5 in Figure 2).

Alignment between the DoD Digital Engineering Strategy and industry's viewpoint of the Digital Twin relies on purposeful and collaborative efforts between people. This requires a partnership between DoD and industry where both parties achieve their values. To enable this relationship, the organizations supporting this position paper are the industry voice and continue to work collaboratively with DoD. This partnership takes many different relationships: some direct (DoD and a specific organization), some collaborative (DoD and a working group) and some indirect (DoD and professional societies).

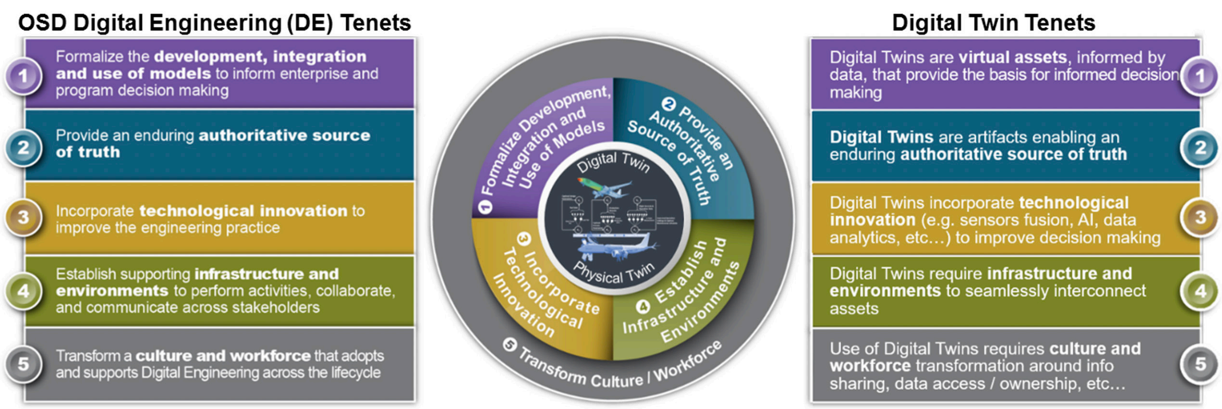

Figure 2. Digital Twin Alignment with the Office of the Secretary of Defense Digital Engineering Strategy [5].