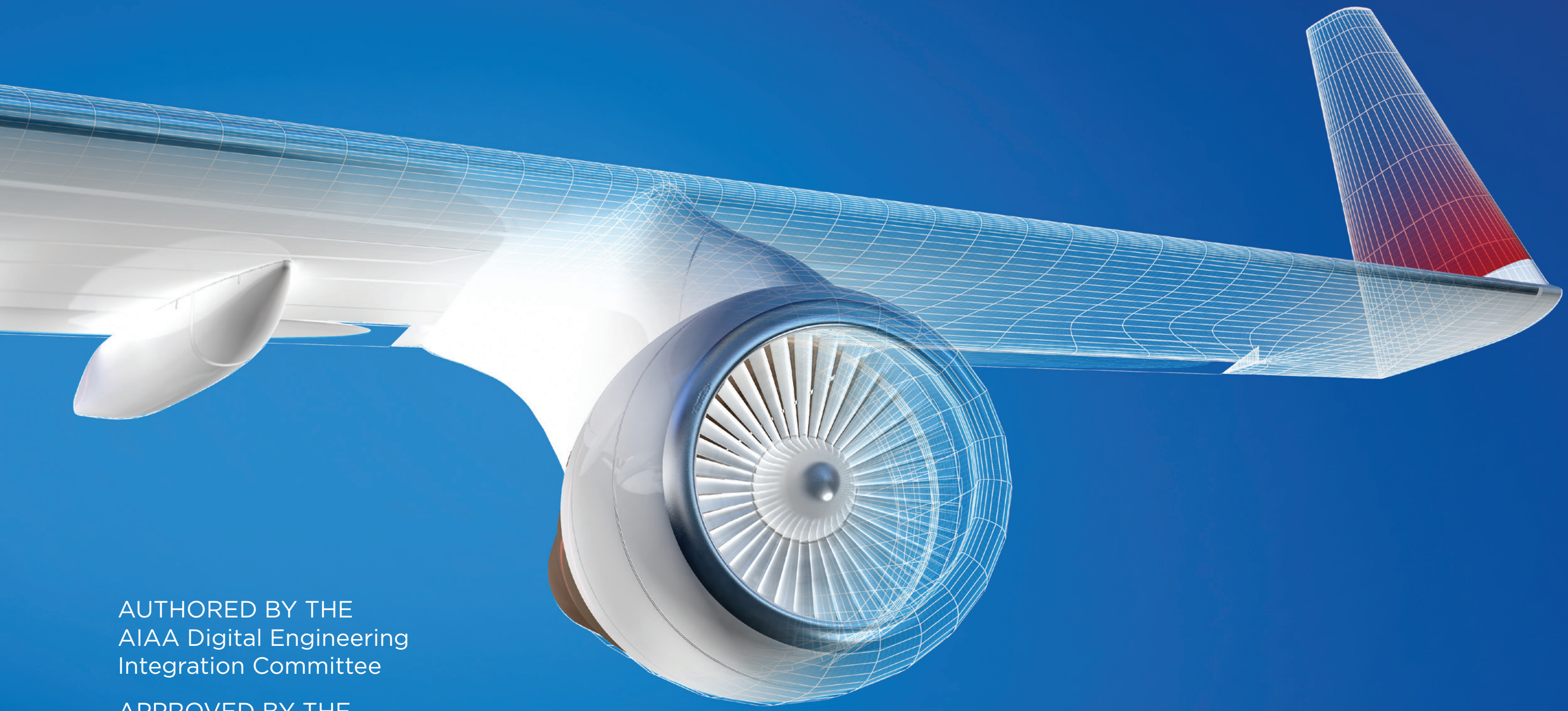
An AIAA, AIA, and NAFEMS Implementation Paper

DIGITAL TWIN:

REFERENCE MODEL, REALIZATIONS & RECOMMENDATIONS



AUTHORED BY THE
AIAA Digital Engineering
Integration Committee

APPROVED BY THE
AIAA Public Policy Committee

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Statement of Attribution

This paper was drafted over the spring, summer and fall of 2021, reviewed in the spring of 2022, approved by the American Institute of Aeronautics and Astronautics (AIAA) Public Policy Committee in fall of 2022, the Aerospace Industries Association (AIA) Technical Operations Council in spring of 2022 and the Americas Regional Steering Committee of the International Association for the Engineering Modelling, Analysis and Simulation Community (NAFEMS) in spring of 2022. AIAA, AIA, NAFEMS, and the paper authors would like to acknowledge the support from the following organizations as substantial contributors to this paper and partners in realizing its recommended outcomes:

- The International Council on Systems Engineering (INCOSE) Model-Based Systems Engineering (MBSE) Patterns Working Group, and
- The Digital Twin Consortium, a community of the Object Management Group (OMG).

This paper is the result of a joint effort from a number of organizations. The AIAA Digital Engineering Integration Committee (DEIC) integrated the organizational authorships of multiple sections. The generic reference model described in this paper was authored by the INCOSE Patterns Based Systems Engineering Working Group and tailored for the Digital Twins presented in this paper. The eight real-world Digital Twins use cases discussed in this paper were authored by Northrop Grumman (Cygnus case study), NASA Integrated Computational Materials Engineering (ICME) Optimization of Advanced Composite Components of the Aurora D8 Aircraft case study), Vanderbilt University (Rotorcraft Component Digital Twin case study), STEP Tools, Inc. (Manufacturing Digital Twin Family case study), the Boeing Company (Smarter Seat Certification Testing case study), the Georgia Institute of Technology (Kendeda Building case study), General Electric (Digital Ghost case study) and Turkish Aerospace (Iron Bird Digital Twin case study).

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Executive Summary

Digital Twins are continuously developed across a wide number of applications and industries. While this position paper represents a testimony to the benefits and opportunities that Digital Twins provide [1] (e.g., reduced cost and cycle time, de-risked and reduced physical testing, improved product design and quality, better descriptive and predictive insight, improved training and sustainment, etc.), their development, maintenance, and evolution still face major challenges [2]. Most past and current efforts focusing on the development of Digital Twins have relied on ad hoc approaches, where most of the efforts start with building models without properly framing the problem [3, 4]. More importantly it has led to the development of models that provide a solution to the wrong problem and consequently fail to address the core questions and needs of the stakeholders [3]. The development and implementation of Digital Twins also lack standardization [5], instead relying on custom methods and technologies [6], which in turns leads to a lack of consistency in their description and implementation, as well as limited interoperability across applications, tools, and disciplines [6, 7]. The development of Digital Twins has been plagued by a lack of scalable approaches, leading to implementations that are highly specialized and require considerable resources in terms of subject matter expertise [6]. The development of standardized methodologies has been identified as a means to unleash the full potential of Digital Twins [5-7] and increase their adoption across a wider range of disciplines and applications [6].

To this end, and in consistency with the Aerospace Industry position paper on Digital Twins that AIAA and AIA published in December of 2020 [1], the objective of this follow-on paper which has also been developed by members from academia, industry, and government is four-fold:

1. To present a generic reference model for describing how Digital Twins integrate with the broader digital enterprise and for informing broader benefit realizations from Digital Twins in a consistent and scalable way,
2. To highlight a cross section of real and tangible Digital Twin case studies that show realization progress and how each example can be represented by the proposed generic reference model,
3. To provide Aerospace Industry recommendations for what academia, industry and government can do together to accelerate realization of value from Digital Twin technology, and
4. To propose specific next steps toward Digital Twin implementation of the noted recommendations through the establishment of an appropriate Aerospace Digital Transformation Consortium (ADTC) to launch an initial pathfinder effort on Joint All Domain Command & Control (JADC2).

This paper is intended for practitioners interested in the development and implementation of Digital Twins as a means to realize value. Finally, while the authors recognize the critical role that Modeling and Simulation (M&S) plays in the development of Digital Twins, M&S is not the direct focus of this paper. Similarly, while an important research area, the issues around data availability, data accessibility, and data update frequency between physical and virtual assets are not treated in this paper.

1 Purpose

This paper builds on the unified Aerospace Industry position paper on the definition and value of Digital Twins presented in [1] and in particular the identified need for tools, methods, and best practices to accelerate the understanding, adoption, and broader realization of Digital Twins.

Digital Twins, which are defined in [1] as virtual representations of connected physical assets, are continuously being developed across a wide number of applications and industries. While this represents a testimony to the benefits and opportunities Digital Twins provide (e.g., reduced cost and cycle time, de-risked and reduced physical testing, improved product design and quality, better descriptive and predictive insight, improved training and sustainment, etc.), their development, maintenance and evolution still face major challenges [2]. In particular, it has been observed that the development of Digital Twins suffers from a lack of problem framing. Hence, most past and current efforts focusing on the development of Digital Twins have relied on ad hoc approaches, where most of the efforts start with building models without properly framing the problem [3, 4]. Such approaches have commonly resulted in poor model calibration due to a lack of appropriate data and a lack of interoperability and model reusability. More importantly it has led to the development of models that provide a solution to the wrong problem and consequently fail to address the core questions and needs of the stakeholders [3]. The development and implementation of Digital Twins also lack standardization [5], instead relying on custom methods and technologies [6], which in turn leads to a lack of consistency in their description and implementation, as well as limited interoperability across applications, tools, and disciplines [6, 7]. Finally, the development of Digital Twins has been plagued by a lack of scalable approaches, leading to implementations that are highly specialized and require considerable resources in terms of subject matter expertise [6].

The development of standardized methodologies (processes and frameworks) has been identified as a means to unleash the full potential of Digital Twins [5, 7] and increase their adoption across a wider range of disciplines and applications [6].

To that end, this paper presents a domain agnostic and descriptive reference model, which builds on recognized industry practices and guidelines, to support the planning, description, and analysis of Digital Twins. In doing so, this paper provides a reference model for describing how Digital Twins integrate with the broader digital enterprise. In particular, the INCOSE Agile Systems Engineering Life Cycle Management (ASELCM) Ecosystem reference model presented in Section 2 provides a descriptive, non-prescriptive reference model for expressing local and environmental constraints, resources, and goals, key interactions and roles, requirements, and solutions for planning, analyzing, implementing, and managing the evolution of the Digital Twin in its system context. Section 3 describes real-world examples of aerospace Digital Twin use cases provided by an AIAA industry and academic team. Section 4 provides common views on how the generic reference model supports the various use case applications. Finally, Sections 5, 6, and 7 provide recommendations for a coordinating body to help secure and further benefits, and further discusses next steps on how to realize value from Digital Twins more broadly.

2 Descriptive Reference Model for Digital Twins

This section summarizes key aspects of a descriptive (not prescriptive) reference model for Digital Twins. Why is this necessary? The reference model describes a uniform set of concepts which all Digital Twins have in common (although to varying degrees and through varied implementations). Individual concrete example Digital Twins are of great interest and summarized in the case studies of this paper—but having a common underlying ontological framework allows understanding individual examples through a unifying lens. Defining the meaning of “Digital Twin” in a single sentence or short paragraph has real value but is less complete than such a descriptive reference model. A leading analogous example in data communication networks is the use of the Open Systems Interconnections (OSI) Reference Model as a framework for describing diverse communication protocols, using a uniform descriptive framework that delineates the configurable underlying concepts common across diverse specific networks and protocols [8]. In the absence of such a common reference model, describing individual communication networks and protocols is far less informative—because we have not described ***what they are examples of***. Ultimately, such a reference framework should be the most compact ontology describing the full set of concepts essential to Digital Twins.

The reference model being used is a configurable Model-Based Systems Engineering (MBSE) “pattern” used by the International Council on Systems Engineering (INCOSE) MBSE Patterns Working Group to describe innovation ecosystems. Its purpose is to aid in understanding their agility, adaptability, use of underlying information, demonstration of ecosystem-level learning, and overall performance, including obstacles and challenges. The reference model has been called the Agile Systems Engineering Life Cycle Management (ASELCM) Pattern. It was used in a study series of INCOSE publications to improve understanding of patterns of ecosystem agility in a systems engineering context [9–13]. The same reference model is also being used in another AIAA position paper to describe the Digital Thread [14].

The reference model addresses the set of system life cycle management challenges inherent to innovation and engineering of systems, as described in [15] and [16]. Indeed, it was in aerospace that these system challenges first became evident, leading to the early history of formal systems engineering. At a higher level, they can be viewed through the lens of observable systems phenomena present in the foundations of systems engineering, key examples of which are summarized in Table 1 [17].

Part of the minimal description of any Digital Twin includes a description of its intended purpose, use, application, KPIs, or benefits sought. Like any system, the Digital Twin system itself is embedded in a larger context (enterprise, engineering organization, factory, operations setting, etc.) that must be referenced to explain the purpose of a specific Digital Twin. Accordingly, the reference framework used here is larger than the Digital Twin itself, because it summarizes the (configurable) library of different (ISO 15288) life cycle management purposes that any given Digital Twin could be expected to serve.

Both engineered system products and the system of innovation itself (including engineering, production, distribution, and sustainment) are subject to the set of system life cycle management challenges. It is thus important to understand how they are addressed by a Digital Twin. Highlights of the ASELCM reference pattern that are relevant for the improved understanding of the Digital Twin include the following six aspects:

1. components of the reference model,
2. support for the business goals and processes,
3. consistency management,
4. Digital Twin's role in group learning,
5. acquiring and improving Digital Twin and other enterprise capabilities, and
6. digital transformation readiness.

Each of these is described in further detail below.

1. **Components of the reference model include the following selection:**
    a. Multi-level logical reference architecture. Figures 1, 2, and 3 represent the first three decomposition levels of the logical architecture of the reference model, ultimately separating the roles played by Digital Twin information classes from the business and technical processes that produce and consume that information. The blocks shown represent generic configurable logical roles (behaviors), not specific methods, until they are configured. Prominent in this decomposition are three system reference boundaries:
        i. **System 1**: The **Engineered System**, at any time in its life cycle. This may be any system of interest that is subject to research and development, engineering, production, distribution, deployment, utilization, sustainment, and retirement, including manufactured products as well as service offerings.
        ii. **System 2**: The **Life Cycle Domain System**, which is the environment with which the Engineered System interacts across its life cycle. This includes all the life cycle management systems responsible for the Engineered System (engineering, manufacturing, distribution, operations, sustainment, etc.). System 2 is responsible for observing and learning about System 1 and its environment, not just engineering and deploying it. A Digital Twin for System 1 is a subsystem of System 2, which also includes the users of that Digital Twin.
        iii. **System 3**: The **Innovation Ecosystem**, which is the environment with which System 2 interacts across its own life cycle. It includes the life cycle management system that is responsible for planning, deploying, and evolving the System 2 life cycle management system. System 3 is responsible for observing and learning about System 2 and its environment, not just planning and deploying it. The planning and deployment of a Digital Twin for System 1 is a responsibility of System 3. This AIAA paper is an example of a System 3 activity. Similarly, there are many activities of other technical societies that are intended to improve the understanding and implementation of future System 2s of the world.
    b. **Stakeholder Features**: Figure 4 represents the library of ecosystem capabilities, configurable as they may or may not be present, to varying degrees, for a given ecosystem. These are configured (populated, and attribute valued) to represent specific cases. The illustrated features include an explicit Digital Twin feature, as well as other (e.g., ISO 15288 [16]; Agile SE [10-13]; etc.) capabilities that can be enhanced by the Digital Twin (e.g., Verification by Analysis and Simulation, Decision-Making, etc.).
    c. **Functional Interactions**: A library of configurable Interactions between the logical architecture roles, through which the capabilities of the

   Stakeholder Features are delivered. Many of these Interactions involve the Digital Twin information classes, shown in Figure 3 and central to the Digital Twin. The overall reference pattern emphasizes information roles (the lower half of Figure 3 in balance with process roles (the upper half of Figure 3).

   d. **Interfaces and Systems of Access** (SOAs): Details within the Reference Model include the Interfaces through which the Functional Interactions occur. As shown in Figure 5, each Interface represents a relationship between (1) a system, which presents the Interface, (2) a set of Input-Outputs, which pass through the Interface, (3) a set of Interaction(s), which represent behavior at the interface, and (4) a System of Access, which is the intermediate media over which the interaction occurs. SOAs relevant to the Digital Twin may typically include Sensors, Actuators, Connectors and Cabling, Wireless and Wired Networks, User Interfaces, Application Programming Interfaces (APIs), etc.

   e. **Design Components:** The entities to which the logical roles above are allocated in a given situation, so that they may be performed by technical components (e.g., IT hardware, software, facilities, information artifacts), individual humans, and enterprise organizations.

   f. **Representation**: The Reference Model is represented as a configurable S*Pattern, (a configurable, reusable, reference model that is independent of specific modeling languages and tools [18]) including a mapping to a system model implementation in OMG SysML (a widely used consensus based standard systems modeling language [19, 20]).

2. **Support for the Business Goals and Processes** of the Enterprise, Supply Chain, or Business Ecosystem, and their Stakeholders:

   a. **Information Roles**: Referring to Figure 3, instances of the underlying information roles in the lower half of the figure, and the Consistency Management role above them all combine to support the higher-level Life Cycle Management Business Processes at the top of the figure. This part of the pattern supports understanding how the underlying Digital Twin roles support performance of the business processes they are intended to improve. Configuring the Business Processes allows them to represent the local project, enterprise, supply chain, or ecosystem. Typical business process roles would include the life cycle management processes of ISO 15288, but may be enterprise-specific.

   b. **Process Roles**: Figure 3 also shows the roles of Stakeholder Advocates being connected through the appropriate Business Processes.

3. **Consistency Management** as a paradigm for Digital Twin's contribution to Engineering and Life Cycle Management:

   a. **Completeness and Fidelity**: The very name "Digital Twin" calls upon intuitive recognition that there is some type of "sameness" when comparing the Twin's computational simulation and the system (System 1) that it simulates. Only some aspects of the simulated system are expected to be "mirrored" by its Digital Twin (the completeness factor)—but for those aspects, there is also an expectation of some form of "consistency" between the two —it is fidelity of the Digital Twin in representing the system it simulates. Moreover, there is the expectation of known, managed credibility of the Twin as to that fidelity for the aspects simulated.

   b. **Model VVUQ**: The management of that Digital Twin credibility leads to the subjects of virtual model verification, validation, and uncertainty quantification (model VVUQ). This is embedded in the broader subjects of model credibility assessment using Credibility Assessment Frameworks (CAFs), and credibility management across the life cycle of the Digital Twin model. These apply to data-driven as well as physics-based models.

   c. **Role of the Digital Twin**: The "Consistency Management" term arises from the larger ecosystem framework in which a Digital Twin is embedded, and it turns out that the simulation Twin's "mirroring" of the system being simulated is only one of many other kinds of consistencies that are managed in the overall ecosystem of any innovation enterprise, supply chain, or institution. Although those other types of consistency are outside the scope of a Digital Twin, the overall fabric of those consistencies is a vital perspective that planners of Digital Twins should understand, as the Twin must support other consistencies. For example, a Digital Twin may be used to verify that a planned product configuration change will satisfy some new behavior requirements, thereby assisting the designer in checking the consistency of a new product configuration with new requirements. One way to understand the larger role of Digital Twins in supporting different types of consistency management is to recognize the roles of a Digital Twin within the larger set of roles of a Digital Thread [14].

d. **Examples of Consistency Management**: A key example of the above is illustrated by Figure 6, which is about two different kinds of consistencies. On the left side of that diagram, we see the questions asked by simulation specialists about the verification and validation of a simulation model used as a Digital Twin describing a proposed product design for use in evaluating that design against the product requirements. The consistency questions of model V&V on the left side of the diagram are about the fidelity with which the simulation represents (say) the actual behavior of a proposed design. By contrast, the right side of Figure 6 asks a different set of questions about a different consistency, which are whether the proposed design of a product will satisfy the specified product requirements, and whether those product requirements are indeed a valid description of what the product stakeholders really need. These right-side questions and consistency are outside the scope of the Digital Twin. However, the Digital Twin's simulation capability will nevertheless be used to help answer the right-side design questions, so it is inside the scope of the application of the Digital Twin! For more examples of the other life cycle consistencies, refer to [14].

e. **Credibility Oversight**: Given all the attention by the modeling and simulation community to "authoritative sources of truth" in the information base, the reference model also helps to highlight the three (often inconsistent) "external" sources of credibility or authority. These are highlighted in Figure 7: (T1) What Stakeholder requests tell us; (T2) What Patterns of Experience from physical sciences, engineering, and past projects tell us; and (T3) What Empirical Observations (measurements) from the real world tell us.

f. Given the inherent conflicts of those three sources of information, it should be understood that a key part of Consistency Management is "reconciliation" of information that is fundamentally conflicting, and not for information-centric reasons of model encoding errors. The related skills of judgment and compromise tend to reinforce the recognition that much of the Consistency Management role is performed by skilled humans. Figure 3 illustrates that generic role, whether performed by humans, machines, or hybrid combinations, and surrounded by seven other roles played by information, along with humans and machines.

g. **Information Roles**: Because the Digital Twin offers to provide the four information roles illustrated in Figure 3 in improved form, there is reason to demand and expect improved Consistency Management. Examples of that improvement vision can be found in Advanced Tooling and representations to support Consistency Management: (I) Semi-automatic generation of credible models from validated patterns [21]; (II) Automated checking of models using semantic technologies [22-25]; (III) Use of formalized Metadata Wrappers, Consistency Signatures, and Credibility Assessment Frameworks to support human and automated understanding of models and what is known about their consistency or inconsistency; (IV) Use of artificial intelligence and machine learning as an aid to consistency evaluation in partnership with human judgment for reconciliations.

h. **Managed Digital Twin System Boundary**: By illustrating the system boundary of the Managed Digital Twin, Figure 8 summarizes the emphasis on the credibility of the Digital Twin simulation in particular, and other forms of Consistency Management across the Digital Thread in general [14]. This is through the performance of Consistency Management on behalf of the higher-level System Life Cycle Business Processes at the top of the figure. This includes the information roles played by not only the managed simulation Model of the Twin, but also generated Datasets, Model Metadata supporting the provenance and credibility assessment of the Twin (including use of Credibility Assessment Frameworks), requirements on the model, and its consistency signature, and general Model-based Patterns of trusted Intellectual Property (IP) from which specific simulation models are configured.

4. **The Digital Twin's Role in Group Learning**:
    a. Phenomenon 3 of Table 1, Figure 2, and Figure 3 emphasize learning at a group level. "Learning" includes the accumulation of information, as well as improvement of performance based on past experience. Traditional descriptions of the SE life cycle processes (e.g., ISO 15288 [16], INCOSE SE Handbook [15], etc.) describe all the actions for generating all the information needed across the life cycle, but they are relatively silent on the question, "What about what we already know?", leaving the management of balancing newly acquired information versus existing information for separate consideration. The Reference Model makes explicit the two aspects by its split of System 2 (Figure 2) into the role of turning what is known into the product in successful service, and the separate role of learning what is not known. The interpretation encouraged here is that the Digital Twin should not simply be viewed as replicating aspects of the system it describes—it should be viewed as representing what the enterprise has learned to date about the modeled system—or at least targeted aspects of it. That includes demonstrating persistence of that learning (versus learning the same things again at high cost). This means more than just persistence of stored information—it means persistence of past learning's impact on future performance.
    b. The left side of System 2 in Figure 2 and Figure 3 is concerned with learning and curating what has been learned for future use, and the right side of System 2 in the same figures is concerned with assuring that what has been previously learned is available (as configurable patterns) for a current project. The combination of these makes it clear that learning is not the accumulation of information—it is the improvement of current and future performance based on past experience. It also emphasizes that effective access to the Digital Twin is essential to its impact. "Learning" here means improved performance, not just accumulation of information.
    c. Digital Twins are learned patterns, and are IP assets, with their own Digital Twin model life cycle, over which model credibility is to be maintained.
5. **Acquiring and Improving Digital Twin and Other Enterprise Capabilities**:
    a. As shown in Figure 1, the planning, specifying, deployment, and ongoing improvement of the Product Digital Twin capability of System 2 is a System 3 role.
    b. The System 2 ecosystem (which is the environment of the System 2 Digital Twin) is a complex system of systems, and arguably always more complex than the System 1 whose real-world life cycle it manages. Accordingly, planning a System 2 Digital Twin capability necessarily requires systems engineering of System 2 itself. That is the role of System 3.
    c. This reference paper and its case studies are all themselves aspects of System 3. One of the following case studies (Manufacturing Twin) is completely focused on the System 3 engineering of the System 2 Digital Twin.
    d. The Reference Model permits the study and planning of a Pre-Digital Twin Environment, and how it will be transformed to a Digital Twin environment, including intermediate transitions, local capabilities, and islands in time or function which are not yet fully connected.
6. **Digital Transformation Readiness**:
    a. A major transitional challenge to the Digital Twin is the preparations and readiness of various organizational roles to produce and consume (effectively utilize) Digital Twin information more effectively than earlier alternatives. This is not just about the organization's readiness to create effective models—it is about the organization's readiness to make effective use of them. That use is increasingly rapidly by parties other than the model authors.
    b. System 3 is responsible for the "readiness" of System 2 to deploy and make effective use of a Digital Twin. For an historical example of the importance of such readiness, consider the 20–30-year historical transition of subtractive metallic manufacturing to a digital model driven capability from the pre-model environment that preceded it.
    c. This includes digital transformation readiness across supply chain enterprise boundaries, wherein readiness of each supply chain

enterprise for its roles in the partially shared Digital Twin are considered.

d. These and other aspects of Digital Transformation Readiness are further described by the application of reference model System 3, as shown in Figure 1 and Figure 2. This can include technical representations of the System 2 Digital Twin, clear business goals and transitional roadmaps, and means to adapt based on what is learned.

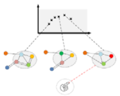
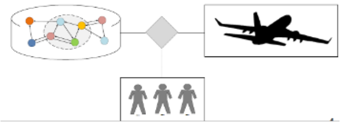
Phenomena Observed	Phenomena Depiction	Phenomena Description
The System Phenomenon (System 1 and 2)		Interacting system components, input/output exchanges, state dependencies and impacts, emerging system-level parameters and behaviors.
The Value Selection Phenomenon (Especially System 2)		Selection of system instance, form, and parameter values.
The Model Trust by Groups Phenomenon (Especially System 2)		Model improvement based on empirical observation, shared learning, and managed model uncertainty, share human trust in a model across a group of interacting humans.

Table 1. Challenging Observable Phenomena—for Both System 1 and System 2

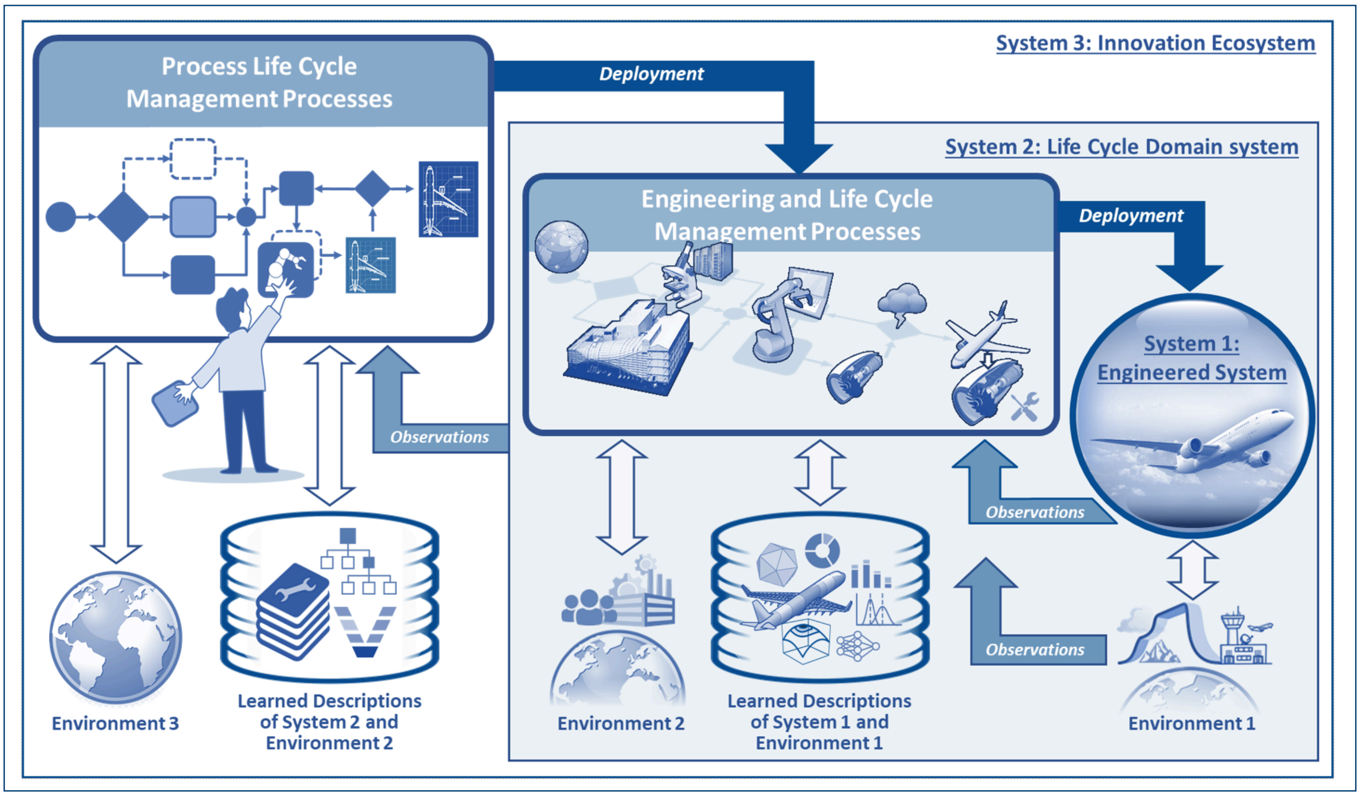


Figure 1. ASELCM Logical Architecture, Level 0

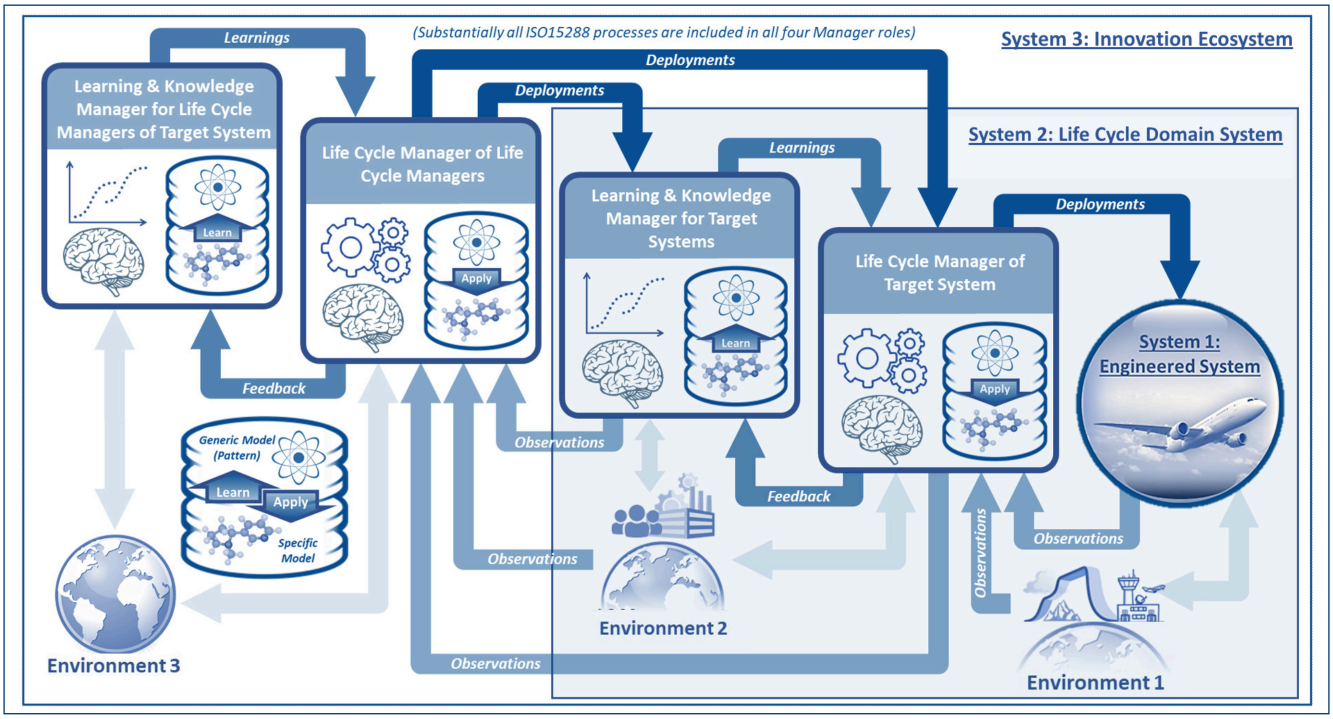


Figure 2. ASELCM Logical Architecture, Level 1

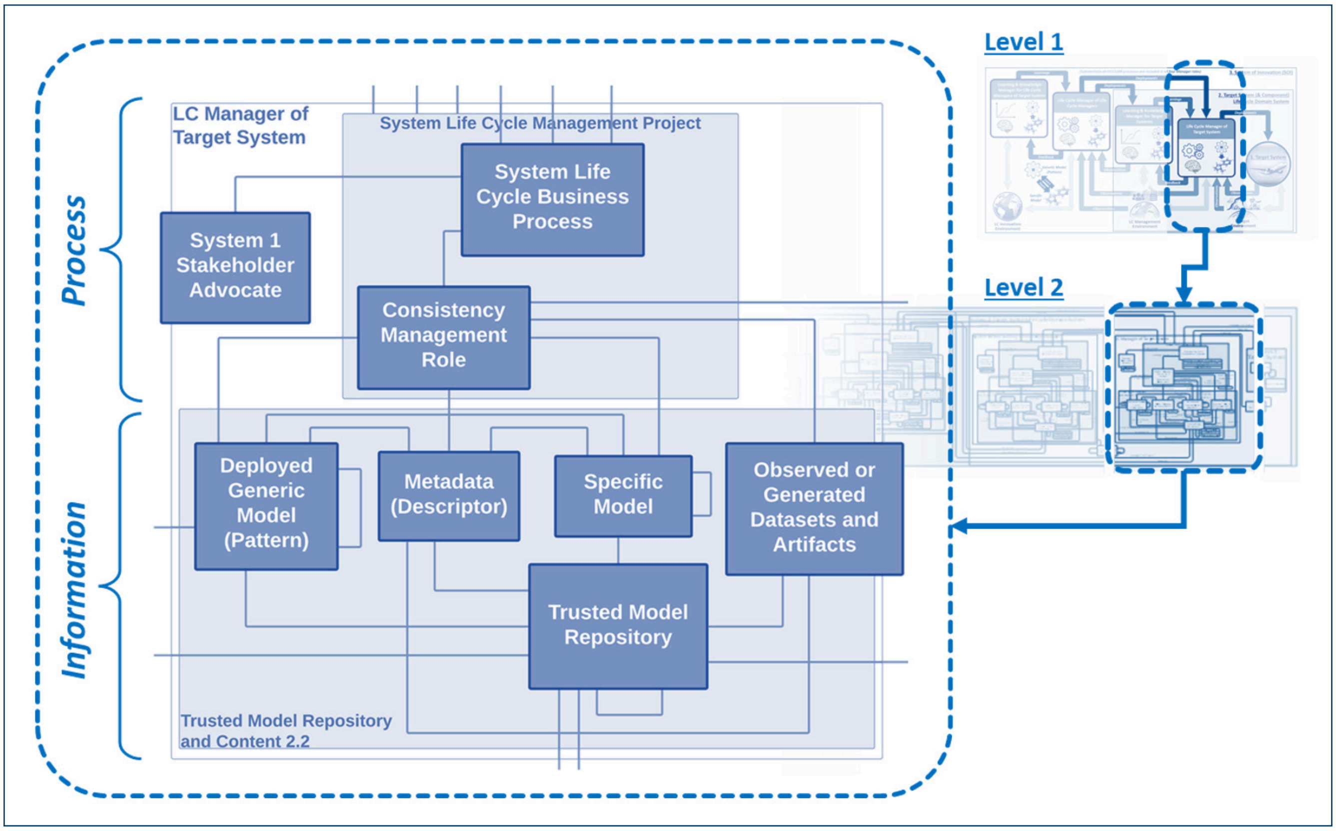


Figure 3. ASELCM Logical Architecture, Level 2

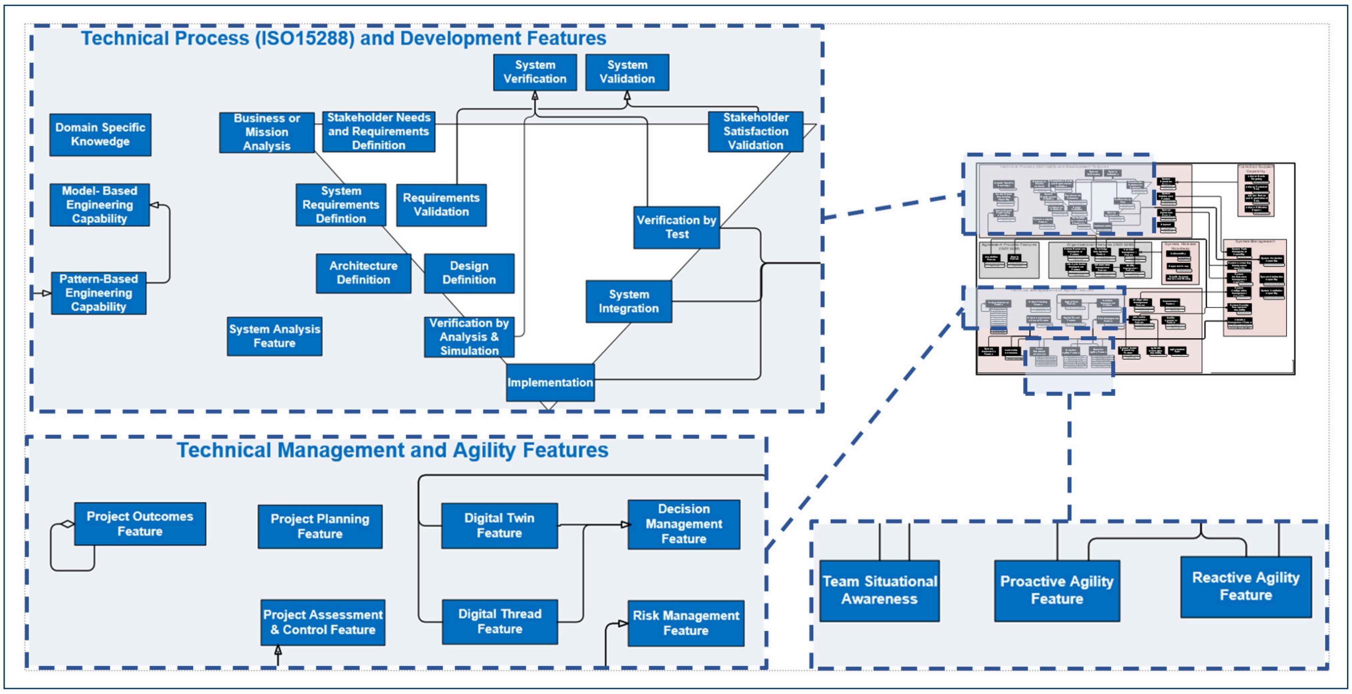


Figure 4. ASELCM Stakeholder Features (Capabilities), for System 2 and 3

A System Inferface is an association of

- A System, which “has” or “presents” the Interface (not always intended!)
- A (set of) Input-Output(s), which “pass through” the Interface;
- A (set of) Interaction(s), which describe “behavior at the Interface”
- A System of Access (SOA), providing the interaction “medium”:

Examples SOAs:

1. Sensors & Actuators
2. Cabling, Wireless Links
3. Tactical Data Links, Link 16
4. Internet, email
5. Doorways (bldg., eqpt.)
6. Hydraulic Hose, Connectors
7. Electr., Mech. Connectors
8. Mechanical & other Tooling
9. Audio/Visual
10. Inermediary people, orgs.
11. Door locks, handles, keys
12. Security access controls
13. Semantic transform maps
14. Encryption/decryption

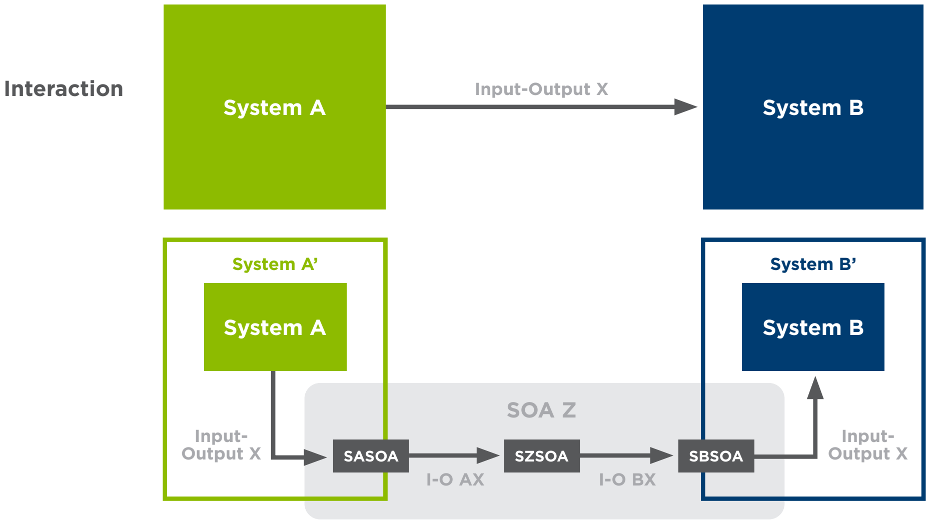
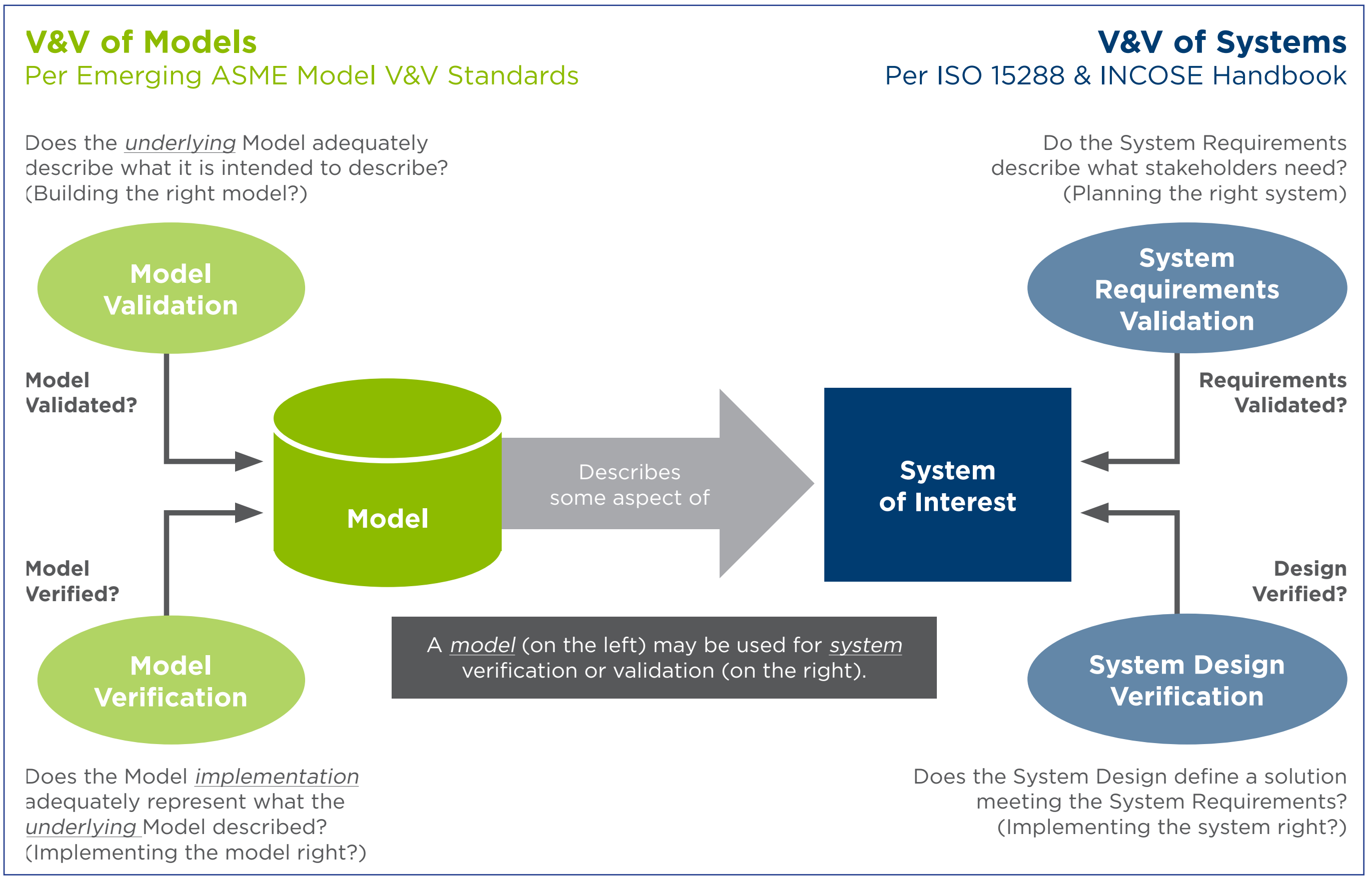


Figure 5. Interfaces and Systems of Access Are Important to Digital Twins



V&V of Models

Per Emerging ASME Model V&V Standards

Does the *underlying* Model adequately describe what it is intended to describe? (Building the right model?)

V&V of Systems

Per ISO 15288 & INCOSE Handbook

Do the System Requirements describe what stakeholders need? (Planning the right system)

A *model* (on the left) may be used for *system* verification or validation (on the right).

Does the Model *implementation* adequately represent what the *underlying* Model described? (Implementing the model right?)

Does the System Design define a solution meeting the System Requirements? (Implementing the system right?)

Figure 6. Two Different Forms of Related but Different “Verification and Validation

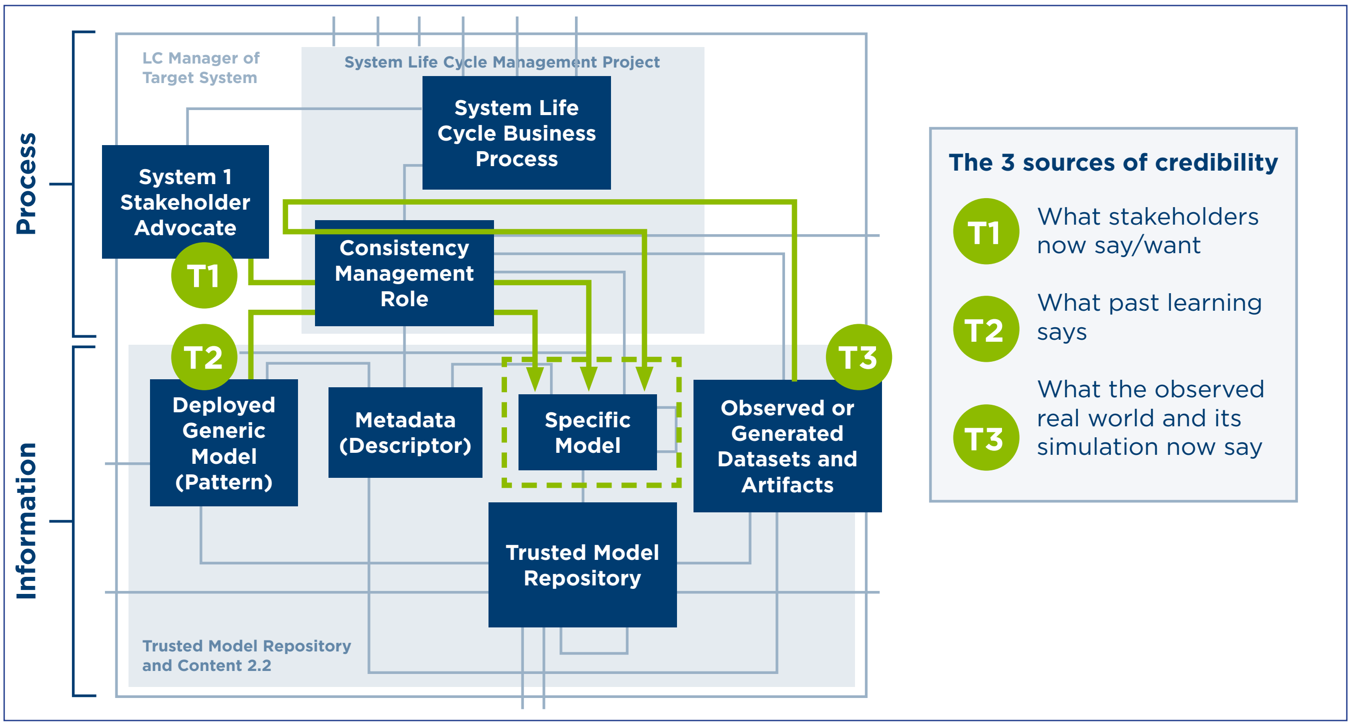


Figure 7. The Three External Sources of Credibility, Authority, and Inconsistency

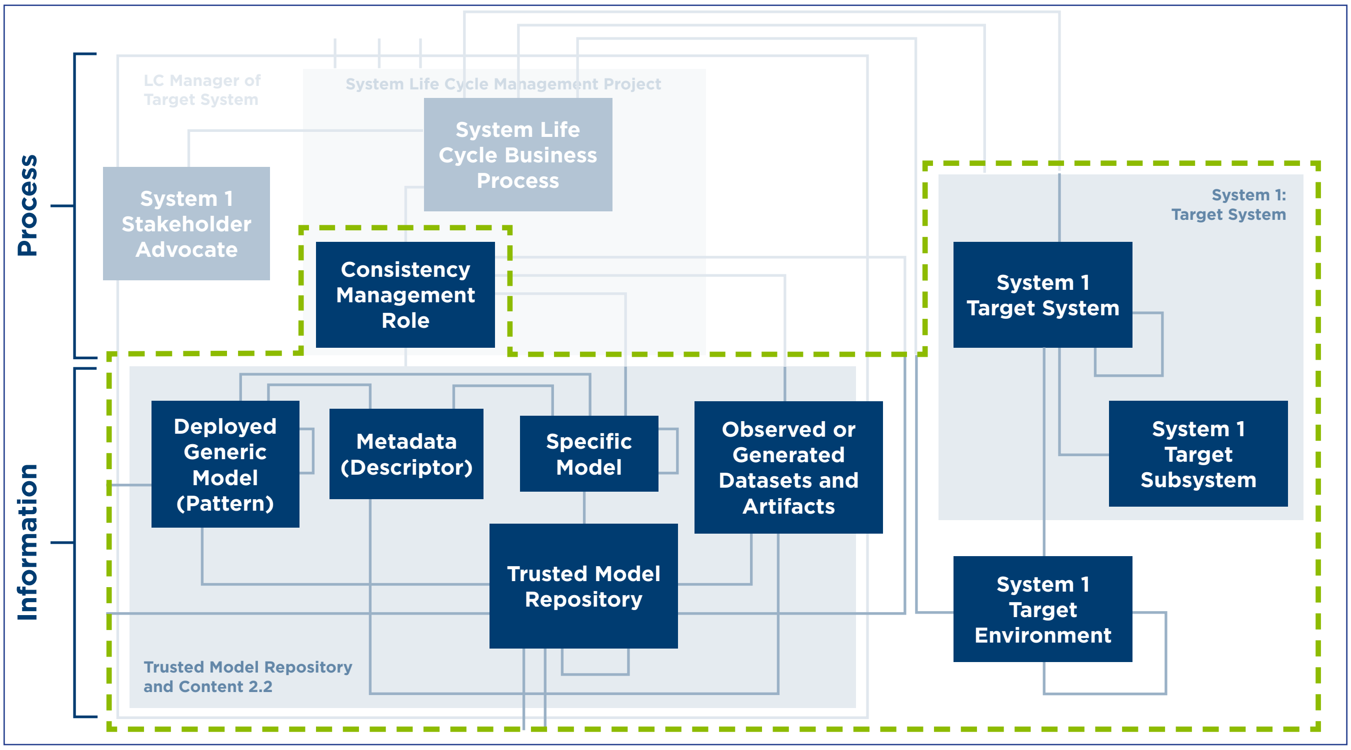


Figure 8. Managed Digital Twin System Boundary

The above Digital Twin connections for the Reference Model are further illustrated in the Digital Twin example applications presented in Sections 3 and 4.

3 Summary of Planning & Realization Case Studies

The case studies introduced below and further detailed in Section 10.2 describe examples of planning or realizations of virtual representations of physical assets over some period of the life cycle. They emphasize the need to carefully identify the intended stakeholders and users of the Digital Twin, their interests and perspectives, as well as the issues to be explored, the questions to be answered, the decisions to be supported by the Digital Twin (i.e., the Digital Twin's purpose), and consequently the type of analyses to be performed (which in turn informs the needs in terms of data and modeling capabilities) [3, 26].

3.1 Cygnus Orbital Ferry Vehicle Digital Twin

The Cygnus Spacecraft is a flight-proven design incorporating elements drawn from Northrop Grumman and its partners' existing, flight-proven spacecraft technologies. Cygnus carries NASA cargo to the ISS and provides all spacecraft functions necessary for safe rendezvous, berthing, unberthing, final descent, and reentry. The Cygnus spacecraft is composed of two main elements the Service Module and the Pressurized Cargo Module. The Service Module provides all utility services to the cargo modules, manages the autonomous rendezvous to the ISS, provides the required resources to allow the mission to be successfully completed, has a structural interface to the launch vehicle and cargo modules, and is integrated at Northrop Grumman's facility. The Pressurized Cargo Module (PCM) provides a pressurized, thermally benign environment for NASA cargo. Northrop Grumman and NASA use Cygnus Digital Twins to predict mission operations and vehicle performance. The vehicles actual performance during a mission updates the Digital Twins to increase accuracy of future predictions. See section 10.2.1 for a detailed description of this use case.

3.2 ICME Optimization of Advanced Composite Components of the Aurora D8 Aircraft

The objective of this activity is to develop an integrated approach to design and optimize the composite Y-joints and composite acreage panels used in the Aurora D8 aircraft. This objective will be achieved by linking material models, structural models, and experiments at multiple length scales. Emphasis will be given to understanding the tie between product design and composite manufacturing. This aeronautical relevant benchmark problem serves to demonstrate the benefits of an Integrated Computational Materials Engineering (ICME) approach. Digital representative models will be generated at every scale, with some or all rising to the level of twin(s) depending upon consistency with scale specific measures of merit. For example, at the nanoscale a molecular dynamic (MD) model of the crosslinked polymer will constitute the digital representation of the bulk resin material during curing. Digital representations of the composite at the microscale, Repeating Volume Elements (RVEs) will be generated using finite element (or alternatively NASMAT [27] representations) so as to be subjected to virtual curing and virtual testing. The digital representations will be used to determine the statistical significance of "Digital Twin(s)" at the microscale that account for random fiber distribution across the composite tows. At the mesoscale the digital representation of the textile composite will be virtually recreated using NASMAT. This Digital Twin(s) will allow the team to study the sensitivity of the material to manufacturing-induced imperfections including, voids, fiber misalignment and microcracks. A Digital Twin of the Y-joint (a subscale macroscale model) will be generated in HyperSizer to optimize the final joint configuration. Finally, a macroscale Digital Twin of the Y-joint and surrounding acreage panels will be recreated in FEMAP and HyperSizer to determine the optimum cost/performance trade-off for the D8 Y-joints and connected composite panels. Data and metadata at each scale (i.e., digital thread) will be stored and tracked to perform sensitivity studies and to highlight potential implementation issues within the ICME platform.

With the emergence of ICME methodologies, computational simulation is moving from a supporting to a leading and driving role in this innovation, in a combinatorial innovation landscape. This application involves the use of modeled composite structures to reduce weight while meeting critical strength requirements and demonstrating new methods for concurrent model-based development across different scales. The result is a multi-scale Digital Twin, or multi-scale integrated collection of Digital Twins. See section 10.2.2 for a detailed description of this use case.

3.3 Rotorcraft Component Digital Twin

Rotorcraft components experience different stress levels based on the flight parameters and intensity of the mission, which in turn dictates the maintenance schedule as well as remaining useful life of the component. Here a component stress-aware rotorcraft flight parameter optimization methodology will be developed by building a Digital Twin for the component of interest. The Digital Twin fuses the information from sensor data, probabilistic diagnosis, probabilistic prognosis, and enables selection of maneuvers that minimize the stress in the critical component. The Digital Twin methodology is demonstrated with a synthetic experiment for a simple flight path.

The Digital Twin paradigm pursued here uses rotorcraft-specific models for inference and operational or maintenance schedule optimization. The Digital Twin-based decision-making process thus advances the state of the art in two different aspects: a) use individual rotorcraft-specific analysis and information for decision making, and b) support proactive operational decisions such as maneuver optimization, in addition to reactive decisions like maintenance and repair.

The three key elements of the proposed Digital Twin-based methodology are: a) development of a probabilistic prognosis model, b) utilization of sensor data to update the health state of the component as well as the prognosis model, and c) flight parameter optimization under uncertainty for a given future mission. See section 10.2.3 for a detailed description of this use case.

3.4 Manufacturing Digital Twin Framework

Digital twins can enable more accurate and more timely modeling of manufacturing results. Modeling Digital Twins during manufacturing is challenging because the processes that must be measured were developed over many years. Adding Digital Twins is only beneficial if further savings can be made without reducing quality or slowing production. There are multiple challenges to making Digital Twins during manufacturing.

- There are real-time requirements that must be met for the data to be captured and processed in time to make adjustments.
- There are precision requirements that must be met if the twins are to add value to existing methods.
- There are modeling requirements that must be met if the twins are to be a detailed representation of the manufactured items.

In the summer of 2020 three case studies were implemented to validate the Digital Twin framework:

1. A robot teaming case study in which multiple robots were used to drill and fill holes for an airframe wing
2. A hole stack-up case study in which a wing is divided into composite, titanium, and aluminum layers.
3. A machine monitoring case study in which a feed override is activated, and impacted tolerances are detected and validated.

All three test cases were developed to show how Digital Twinning can make manufacturing more flexible and accurate. See section 10.2.4 for additional details regarding this use case.

3.5 Smarter Seat Certification Testing Digital Twins

Passenger safety is a critical priority for Boeing commercial airplanes, and seat installations are a key aspect of passenger safety. While seat structural integrity and occupant safety have been historically assured through certification testing, the same level of passenger safety can be achieved by analytical methods due to recent advancement of “Digital Twin” computer modeling and simulation technology. This use case is the result of collaboration between The Boeing Company, seat suppliers, academia, and regulatory agencies to establish standard work instructions for developing Digital Twins for seat dynamic simulation. Use of Digital Twins and model-based engineering is a Boeing digital transformation enabler, and a 2nd century Enterprise Systems (2CES) initiative for Boeing.

Herein, Digital Twins are validated by dynamic tests, and are used to:

- Establish the critical seat installation location and configuration in preparation for dynamic testing.
- Demonstrate continued certification compliance when changes are made to a baseline seat design, where the original seat has established compliance based on dynamic tests.

The airplane seat Digital Twin utilized simulation of seats as a means of regulator (i.e., FAA and EASA) compliance. As such the airplane seat Digital Twin effort developed and demonstrated the capability to build validated simulation models for Certification by Analysis (CbA) [28]. The airplane seat program performed physical testing and validation of Digital Twin models. The development of the Digital Twin of the airplane seat and its implementation focused on safety [29] of the developed physical product. The program focus was not to fully eliminate product testing, but instead to significantly reduce testing by leveraging insight gained through the Digital Twin. The simulated testing environment allowed dynamic requirements verification on passenger seat assemblies. See section 10.2.5 for additional details regarding this use case.

3.6 Georgia Tech's Kendeda Building Digital Twin

A Digital Twin was created by the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech (GT) in support of GT's Kendeda Building for Innovative Sustainable Design (KBISD). Use of the Digital Twin made it possible for KBISD to receive certification in 2021 as a "Living Building" from the International Living Futures Institute (ILFI) [30]. The Digital Twin needed to be subjected to the same conditions—weather, occupancy, control schemes—as its real counterpart in order to serve as a baseline for quickly detecting faults that would jeopardize certification. During the 12-month certification period, the Digital Twin was also used to forecast the net "budget" of water and energy through remaining months to gage whether the building might be "programmed" (i.e., planned) for more intensive use by occupants and visitors.

In general, the return on effort to calibrate Digital Twins of building performance can be unattractive, especially when compared to that of other systems like vehicles. The return (or value) is relatively lower because performance requirements around building utilities (e.g., efficiency and comfort) tend to be less demanding than those of vehicle operations (e.g., safety) and thus attract less investment. Finally, the architectures and uses of different buildings are often very diverse, so the potential for model or data reuse across a community of buildings can be limited.

Implementation of this Digital Twin involved the following steps:

- Understand the as-built KBISD system
- Measure actual performance: the inputs and responses in Figure 27
- Model the as-built system
- Integrate models into a Digital Twin and calibrate to observed performance, iterating as necessary by increasing fidelity, exploring alternative modeling approaches, etc. until good convergence is achieved
- Employ the Digital Twin on a periodic basis in reviews with stakeholders, to:
  - o Benchmark performance to identify system and/or data degradation
  - o Run scenarios subjecting the twin to alternative inputs, to answer "what if" questions.

See section 10.2.6 for additional details regarding this use case.

3.7 Digital Ghost – Cybersecurity for Critical Assets Leveraging Digital Twins

Cyber-attacks on high value assets and their associated control systems are a growing threat, increasing at an alarming rate over the past several years. Assets have been disabled, damaged, and even destroyed by malicious cyber actors. Today's security model for control systems focuses on perimeter defense, mostly designed with threat detection in the information technology layer (IT: e.g., computers that store, retrieve, transmit, and manipulate data) and operational technology layer (OT: e.g., direct monitoring devices and communication bus interfaces). While the conventional IT and OT techniques do offer some protection and defense, mostly based on monitoring traffic patterns, the question remains that how an asset owner or operator can maintain critical operations safely if malware becomes embedded in the control system, without shutting down the entire system. A stealthy attack may lay dormant in a system for months waiting to activate and create havoc for the system owner. Similarly, life and equipment efficiency may be unknowingly lost because the operator was unaware of his/her system being compromised. Additionally, sophisticated attacks with knowledge of the system can affect the sensors and actuators signals, while remaining undetected by the conventional IT/OT systems. The scenarios are likely to fool the defense systems based on traffic patterns and without any knowledge of the underlying assets. Finally, generic protection mechanisms offered by today's fault tolerant systems are not enough to provide the resiliency or high availability needed for key infrastructure assets to maintain safe operations during cyber-attacks.

The Digital Ghost, which acts in addition to common IT/OT cybersecurity, offers a defense in depth strategy with the last layer of defense being the physical defense layer. The internal algorithms within the Ghost will alert the asset operator if a malicious attack or physical fault is underway. Additional Ghost features can indicate the point of attack within the system and provide a layer of resiliency by neutralizing the effects allowing the asset to continue operating through an attack.

The differentiating feature of the Digital Ghost comes from the use of a Digital Twin of the asset, which encapsulates the detailed knowledge of the underlying system and the associated control system. These Digital Twins are often created during the design and validation phases for a new asset and are thereafter tuned using rich historical data sets available to GE. Thus, they are the highest fidelity models available for the underlying assets, and their access is limited to the OEMs. The Digital twins are used to extensively simulate all operating conditions and foreseeable attack vectors to train Digital Ghost algorithms, thereby allowing the algorithms to learn very high dimensional boundaries (called decision boundaries or manifolds, which form the separation between normal and abnormal operating space) in a very precise manner. It should be emphasized that methods based on historical data alone would not be able to offer the high degree of accuracy achieved by leveraging the Digital Twin, which gives OEMs like GE a distinct edge in development of the technology. To date, detection has been developed and validated using sophisticated computer models for gas turbines, heat recover steam turbines, steam turbines and generators, building energy management systems, wind turbines, and gas pipeline network systems. Detection accuracies of nearly 99% and false positive rates of 1% have been shown in most cases. Localization is in a similar development state showing excellent results on par with detection. The neutralization algorithm to protect gas turbine against cyber-attacks has shown to be effective when nearly 55% of critical nodes have been compromised. The GE team is continuing to advance the technology and apply it to a wider array of real-world applications. See section 10.2.7 for additional details regarding this use case.

3.8 Iron Bird Digital Twin

Building an aircraft has three main phases: design, manufacturing, and testing. Testing an aircraft is essential and testing accuracy is extremely important. Making these tests under almost real and accepted conditions by authority is needed for certification and to validate your design. Hundreds of testing environment are being used during an aircraft validation and certification activities. Turkish Aerospace designs and builds an aircraft from scratch and develops Flight Control System (FCS) as a subsystem with all system engineering and software development activities. Turkish Aerospace is also responsible for integration of aircraft at final assembly line and completion aircraft level testing. Iron Bird is one of these test environments and an essential tool to validate and verify FCS with actual actuators, hydraulic system, and loads. Iron Bird mainly consist of flight control system with real actuators, harness, software and computer, and hydraulic system with all actual components. Iron bird also has loading system including hydraulic, loading actuators and controllers. Iron bird mainly applies real loads to control surfaces with different parameters for different flight conditions. The FCS and hydraulic system are being tested under real load conditions, also with some hard failure cases (actuator jam, hydraulic failure, etc.) Testing flight control algorithms with software in the loop and hardware in the loop test environments are general approach and using Iron Bird and testing Flight Control System under real loads with actual mechanical and hydraulic system is essential for a fly-by-wire system. Actuators are important and valuable equipment for aircraft industry. They are key elements to control your aircraft. Actuators are also important for test rigs to provide enough power through a requested direction. Actuators and hydraulic system are heart of Iron Bird. Flight control algorithms are being tested on desktop development environment with a generic actuator model with generic backlash and stiffness parameters. To see real action of flight control and observing how stiffness, backlash, and load effect behavior of flight control, almost 1000 hours of flight testing is being run on iron bird. That means so many data are being collected during Iron Bird testing activities. Turkish Aerospace experienced that updating hydraulic and actuator models with the real data will provide a better and realistic testing environment on the desktop for flight control software and decided to create a Digital Twin for Iron Bird and other test rigs. Iron Bird Digital Twin concept provides continuously updating of generic actuator and other mechanical system models with the help of actual data which is being collected in each test. Establishing a real-time connection between sensors on iron bird and Digital Twin environment provided us an environment to test generic actuator and hydraulic models with real test input and to update our models. Actuator and mechanical system behavior may change in time and in different environment conditions but having an updated model for these systems will also help to modify or update current air platform more effectively even in design phase. On the certification basis, having an iron bird and using it for thousands hour of flight is still essential but decreasing number of failed tests on iron bird with the help of Iron Bird Digital Twin will provide effective usage of test rig and decrease time needed to complete iron bird essential tests. That approach will help engineers to validate their design in earlier phases. See section 10.2.8 for additional details regarding this use case.

4 Summary of Reference Model Applications

Table 2 and the diagrams below synthesize how the generic reference model supports the various use case applications presented in Section 3. In particular, Figure 10 through Figure 12 summarize how the use case applications fit together into the different roles necessary for any system.

Case Study	**Reference Model Application**
Cygnus Orbital Ferry Vehicle Digital Twin	The AIAA team reviewed the Digital Twin application created for Northrop Grumman Corporation’s Cygnus family of mission vehicles [31, 32]. From a reference model perspective, with the orbital vehicle viewed as System 1, this System 2 Digital Twin is simulating System 1 performance, during the mission planning, engineering, and operations stages. Relevant reference model System 2 features therefore extend to include Mission Planning, along with Requirements Definition, Digital Twin Feature, and Decision Making.
ICME Optimization of Advanced Composite Components of the Aurora D8 Aircraft	With respect to the reference pattern, this Digital Twin study is active in both System 2 (where models of the different scales are generated and used) and System 3 (where new paradigms of the System 2 work process are described, deployed, and studied). Relevant System 2 features include Digital Twin Feature, Consistency Management, Decision Management Feature, and Verification by Analysis and Simulation Feature. Relevant System 3 features include (as description of the System 2 ecosystem) Business or Mission Analysis, Architecture Definition, and System Transition.
Rotorcraft Component Digital Twin	From a reference model perspective, with the rotorcraft component viewed as System 1, the System 2 Digital Twin is simulating System 1 performance. Relevant ASELCM System 2 features therefore extend to include Business or Mission Analysis, Stakeholder Needs and Requirements Analysis, Design Definition, MBE Capability, and Digital Twin.
Manufacturing Digital Twin Framework	Viewed from the perspective of the generic reference model, System 1 represents the manufactured product and System 2 the product engineering and manufacturing system, the current use case is focused on System 3, where the Digital Twin and manufacturing engineering system is found. The relevant System 3 features therefore include System, Requirements Definition, Architecture Definition, and Design Definition, where the “system” here is the Managed Digital Twin. The relevant System 2 functional roles, to be allocated to design components (hardware, software, people, facilities, etc.), therefore include Consistency Management, the Configured System Model, Empirical Datasets, Descriptive Model Metadata, accumulated simulation Patterns, and the Trusted Model Repository. Standards-based Interfaces and Systems of Access for sensors and actuators associated with the manufacturing system were prominently illustrated within the standards-based ISO23247 descriptive framework. The roles of the Life Cycle Management Business Process and Stakeholder Advocate complete the representation of the supported manufacturing mission.

Smarter Seat Certification Testing Digital Twins	From a reference model perspective, with the airplane seat viewed as System 1, this System 2 Digital Twin is simulating System 1 performance during the mission planning, engineering and operations stages. Relevant reference model System 2 features extend to include Stakeholder needs and requirements analysis, along with Implementation, Verification by analysis and simulation, MBE capability, and Acquisition. Within the reference model framework, the relevant systems 2 functional roles allocated to design components included: • Consistency Management (i.e., regulator, Standards organization, and program teams); • Deployed Parent Patterns (i.e., FEA and system modeling knowledge, aircraft supplier design knowledge); • Pattern Component Models (i.e., LS-Dyna algorithm deployment); • Empirical Datasets (i.e., test and simulation results); and, • Trusted Model Repositories (i.e., IT environments, toolsets).
Georgia Tech's Kendeda Building Digital Twin	With respect to the reference pattern, with the Kendeda building viewed as System 1, this Digital Twin study is active in both System 2 (where models of different scales are generated and used) and System 3 (where new paradigms of the System 2 work processes are described, deployed, and studied). Relevant System 2 features include Business or Mission Analysis, Stakeholder Needs and Requirements Analysis, Design Definition, Verification by Analysis and Simulation, System Transition, and System Performance Management Capability. Relevant System 3 features include Acquisition, Human Resources Management, Business or Mission Analysis, Stakeholder Needs and Requirements Analysis, Design Definition, Implementation, and Transition. This case study is a good example to highlight differences between System 2 and 3 features of the same type; both Systems 2 and 3 have four features that are of the same type but apply to different reference model systems (System 2 or 3).
Digital Ghost – Cybersecurity for Critical Assets Leveraging Digital Twins	With respect to the reference model, a protected critical infrastructure IIOT asset is System 1 includes cybersecurity adversaries. During the design of the protective cybersecurity network for System 1 management, a System 2 Digital Twin simulates normal application-level network traffic consistent with application physics of System 1. This twin is used to train the run-time protective cybersecurity network to recognize probable threats as discriminated from normal traffic.
Iron Bird Digital Twin	From a reference model perspective, with the Iron Bird test rig viewed as System 1, the System 2 Digital Twin is simulating System 1 performance during engineering, system verification and test running activities. The relevant System 2 features therefore include Stakeholder Needs, Verification by Analysis and Simulation, Verification by Test, and Digital Twin.

Table 2. ASELCM Application to the Case Studies

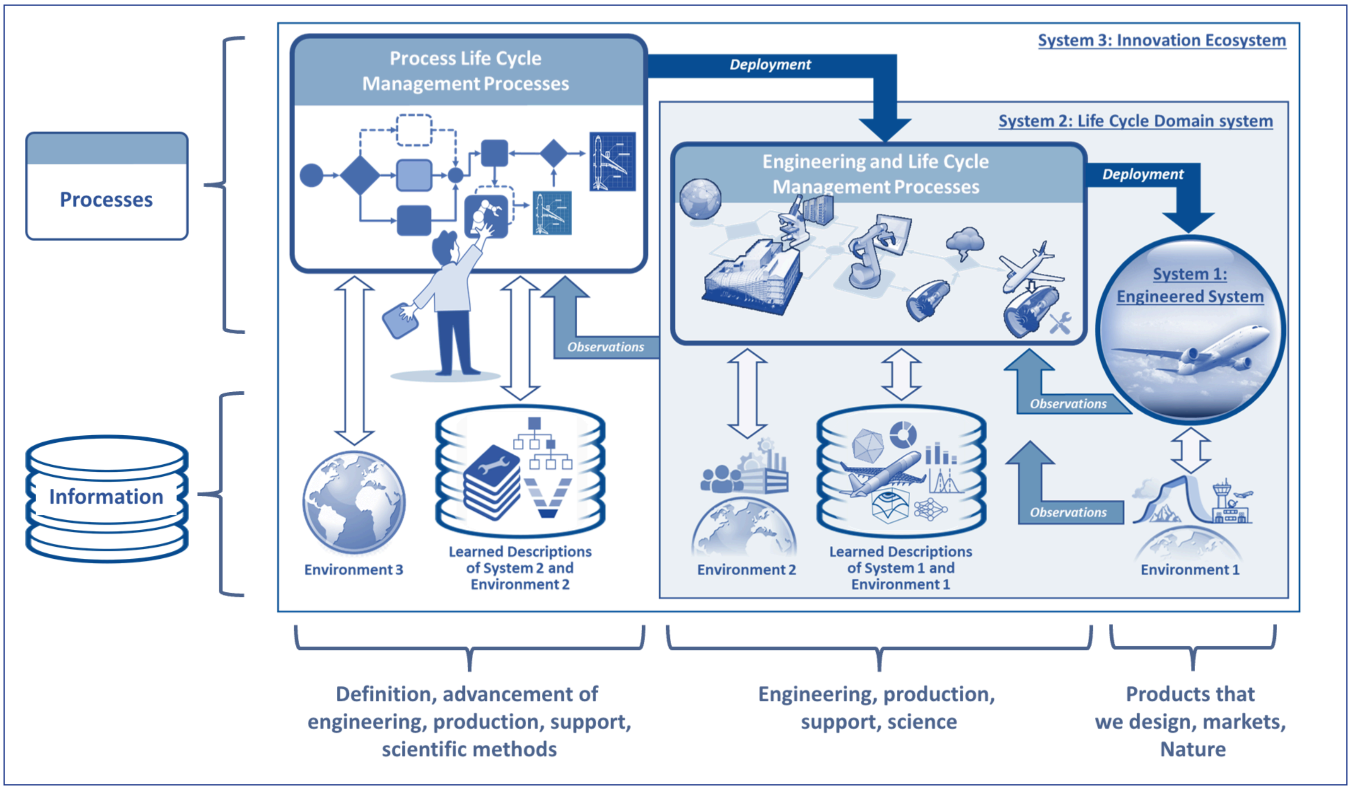


Figure 9. Top-Level View of the ASELCM Pattern

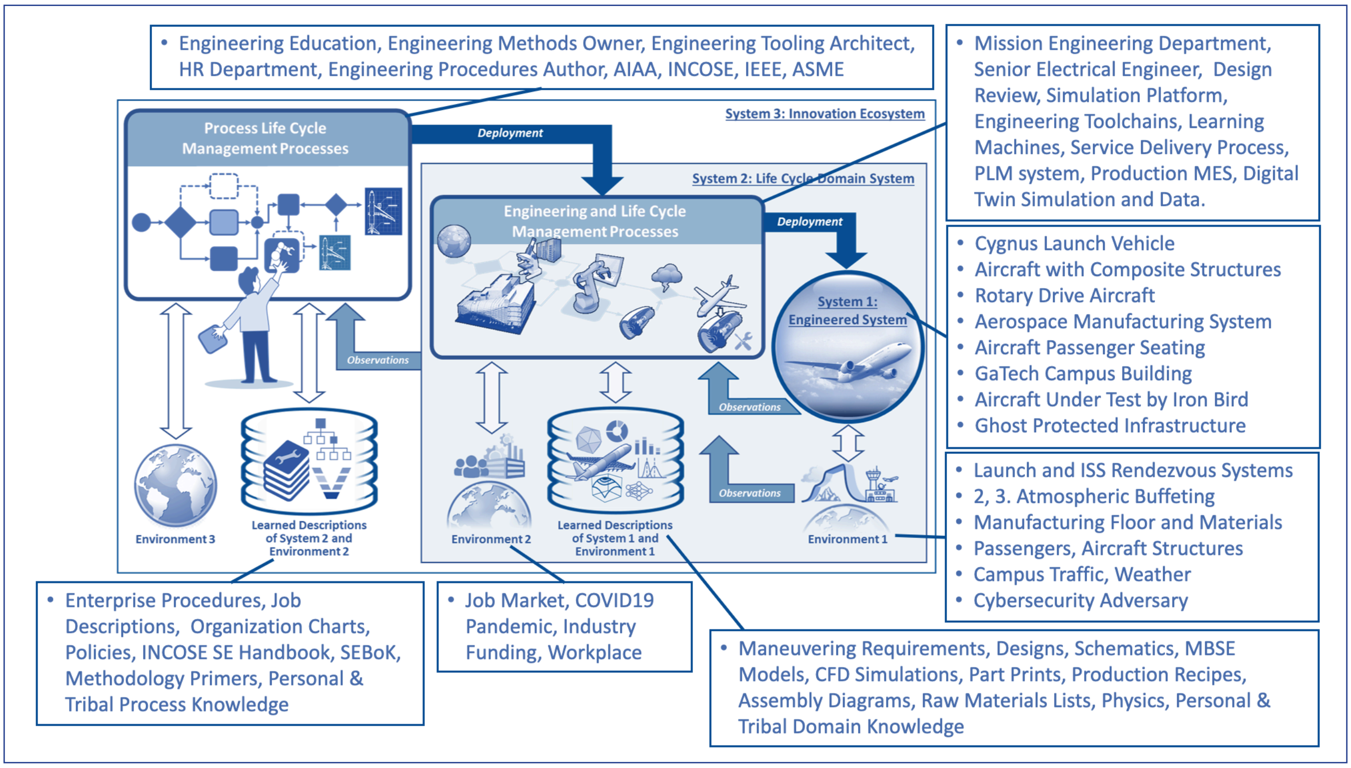


Figure 10. ASELCM Logical Architecture, Level 0 View across the Use Case Applications Considered

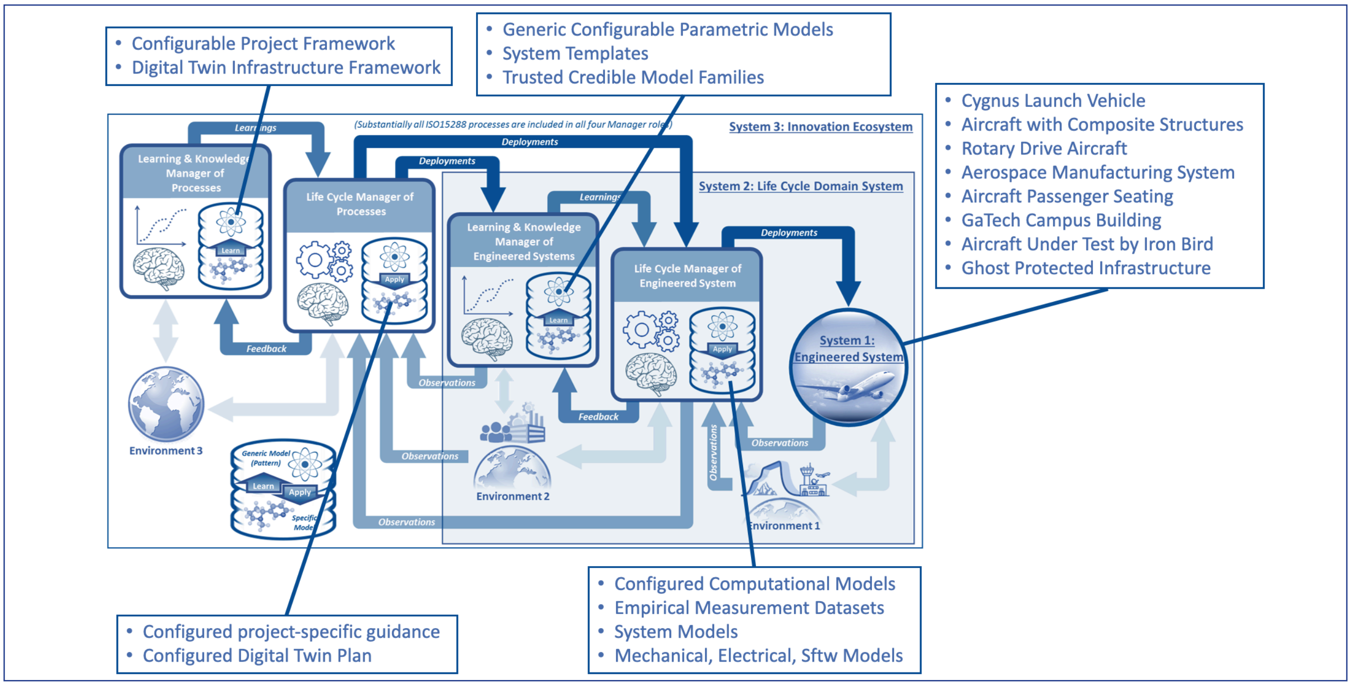


Figure 11. ASELCM Logical Architecture, Level 1 View across the Use Case Applications Considered

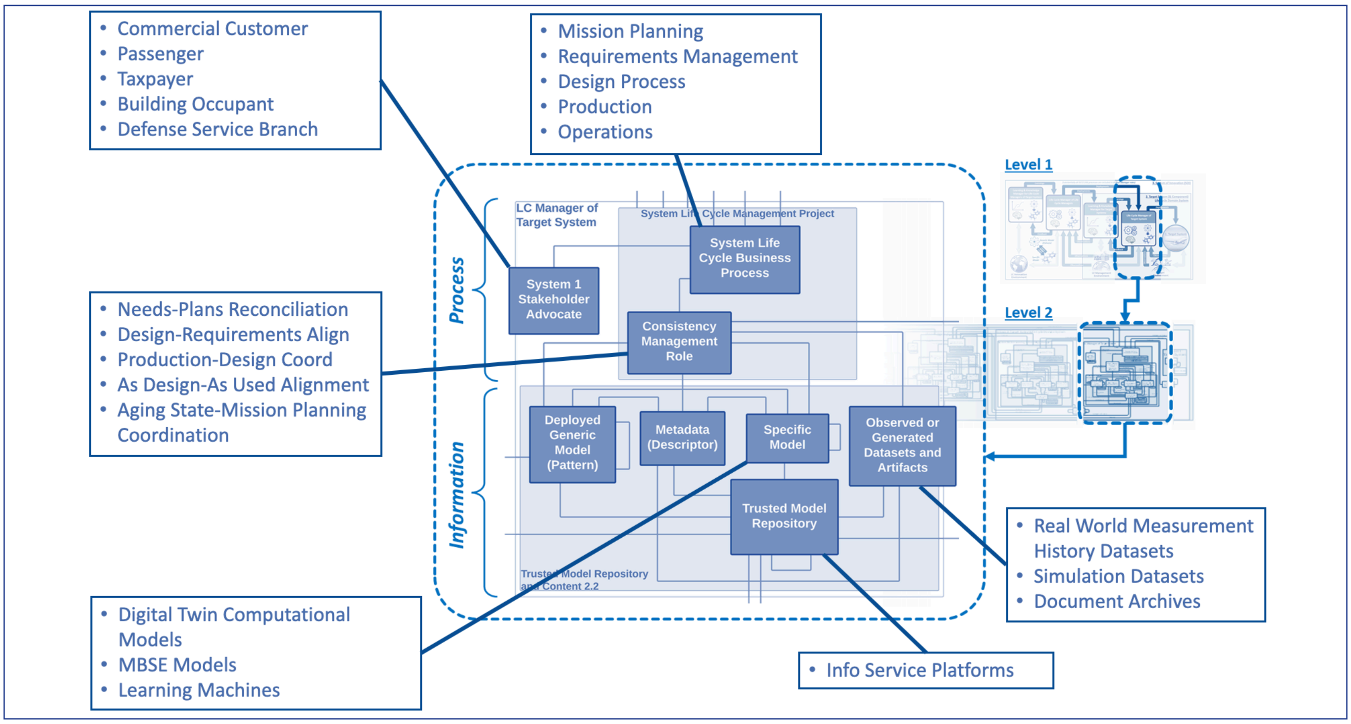


Figure 12. ASELCM Logical Architecture, Level 2 View across the Use Case Applications Considered

Table 3 highlights the role of consistency management for each case study with the left two columns depicting the relevance of each case study to System 1 and System 2 (that is, models managed by Systems 2 and 3).

	Modeled System		Consistency Type Managed	Example Aerospace Application	Example Case Studies							
	System 2 Life Cycle Manager	System 1 Target System			Cygnus Launch Vehicle	Aircraft with Composite Structures	Rotary Drive Aircraft	Aerospace Manufacturing System	Aircraft Passenger Seating	GaTech Campus Building	Digital Ghost	Iron Bird
1		▨	Product Design versus Requirements Consistency	Certification or Pre-certification Verification					▨	▨		▨
2		▨	Product Design versus Requirements Consistency	Multi-Physics Design Concept Verification		▨						
3		▨	Requirements versus Stakeholder Needs and Mission Consistency	Market Coverage Optimization	▨				▨			
4		▨	In-Service Product Use versus Mission Requirements	Mission Planning Product or Use	▨		▨			▨	▨	
5		▨	Product Requirements and Design versus Supplier Product	Initial Acquisition and Subsequent								
6	▨	▨	In-Service Product Maintainability versus Requirements	Improve service Process or Product								
7	▨	▨	Production Consistent with Product Design Specification	Production Quality Control & Yield				▨				
8	▨	▨	Production Consistent with Product Design Specification	Production Throughput, Efficiency				▨				
9	▨		Requirements for Digital Twin Capability versus Twins Plans	Acquiring Digital Twin Capability				▨		▨		
10	▨		Requirements for Digital Thread Capability versus Twins Plans	Acquiring Digital Thread Capability								

Table 3. Configuration Management Applied to the Case Studies

5 Recommendations

This document has presented a generic reference model and framework for describing how Digital Twins integrate with the broader digital enterprise. Furthermore, a subset of Aerospace Industry use cases and case studies were described which demonstrate the relevance and utility of this reference model. The opportunity for benefit realization from Digital Twin, and more broadly Digital Engineering, capability is significant. This work provides the needed context for collaboration and consistency management so the Aerospace Industry as a whole can move out toward realizing the greatest value from Digital Twin implementation.

5.1 Recommendations on Methodology

Recommendations on methodology for planning, implementing, and applying Digital Twins include:

5.1.1 Implementing Digital Twin(s) Demands Enterprise-Level Systems Engineering

Understanding the benefits targeted by the Digital Twin requires understanding certain aspects of the enterprise system in which it is embedded (System 2 in the above reference model). The benefits and promises of the Digital Twin are many, but nearly always involve change across enterprise functional “silos” and life cycle stages. The enterprise, a socio-technical system, can defeat good intentions unless (multi-level) organizational, cultural, incentive, and technical considerations are brought together in an integrated plan and implementation. This includes representing the intended enterprise system in an integrated way that allows these different aspects to be considered together as this is required in the real enterprise. It includes recognition that base patterns inherent to the Digital Twin require configuration to fit the enterprise, supply chain, industry, program, domains, or other considerations. We do not engineer aircraft without integrated representations of the diverse views involved; the Digital Twin embedded in the Enterprise System is similarly complex. This paper has briefly summarized the configurable INCOSE ASELCM Ecosystem reference model (see Section 2) that provides a descriptive, non-prescriptive framework for expressing local and environmental constraints, resources, and goals, key interactions and roles, requirements and solutions, for planning, analyzing, implementing, and managing the evolution of the Digital Twin in its systems context. For example, the related framework encourages us to understand the computational resources (hardware horsepower), sensors and actuators, culture, and change processes. The use of such a common reference framework has the additional benefit of facilitating collaboration across different industry players to advance the overall ecosystem seen by the customer.

5.1.2 Alignment with Related Enterprise Efforts Can Impact Success

During current times, aviation and aerospace enterprises are mid-stream in tackling many programs of change. Some of these are so directly related to the Digital Twin implementation that they should be considered in its planning. One approach is “vertical” integration, where the Digital Twin implementation includes “support for another enterprise program” that emphasizes higher enterprise-level business goals suited to the Digital Twin’s strengths. This can help with justification of Digital Twin investments. Another approach is “horizontal” integration in which the Digital Twin implementation is to “interoperate with another enterprise program” that intersects with shared information systems or people. This can help avoid technical or organizational collision obstacles, and build alliances. Prominent examples of this are current enterprise efforts for Digital Engineering, Model-Based Engineering, the Model-Based Enterprise, the Digital Thread, and Industry 4.0. Finally, all of these programs of change include the challenge of the enterprise’s “readiness” to take on the related changes. The preparations required for different programs of change often overlap, and can share the effort, time, and cost of preparation of staffing, education, and facilities.

5.1.3 Managed Trust in the Ongoing Fidelity of the Digital Twin for Purpose and Over Time Is Essential

Digital Twins can have a wide variety of intended purposes. However, all those purposes will be in support of informing some future decision or action. (If that were not the case, omitting the Digital Twin would have no impact.) This means that the Digital Twin must be trusted as a source of information in a way that is fit to the intended application of the Digital Twin. In some cases, this may involve heavy reliance on the underlying Digital Twin’s fidelity and bear serious consequences if that trust is misplaced. In other cases, the intended application may only consult the Digital Twin as one of several sources of information, or be associated with low impact consequences of inadequate model fidelity. But in all cases, conscious management of the credibility of the Digital Twin as a model of a real system of interest is required. This includes not only the technical tasks of model VVUQ (assuring the Digital Twin itself is accurate enough for the intended purposes). It also includes management of propagation of trust by technical and non-technical staff or extended communities (consider models of weather, climate, epidemics, etc.), where invalid trust as well as invalid mistrust are to be avoided. This article has briefly summarized the related roles of:

a) Disciplined processes of computational model validation, verification, and uncertainty quantification;

b) Credibility Assessment Frameworks (CAFs), describing extended bases for trusting a model that include but go beyond quantitative VVUQ alone;

c) Metadata packages for planning and describing computational models in terms of their intended context of use, scope, provenance, required computational resources and environment, sensor and actuator specifications, technical and stakeholder requirements, and other aspects of managing libraries of trusted computational models as they evolve over their life cycles. This article has noted the use of the universal, configurable Model Characterization Pattern (MCP) for those purposes.

5.1.4 Ongoing Multi-Level Group Learning Is Central to the Digital Twin

The underlying computational models of Digital Twins represent a key form of learning about the real-world systems and system environments that they describe—just as they have represented learning in the related history of models in the physical sciences. Whether models constructed by humans from the hard-won lessons of experience, experiment/observation, costly mistakes, and theoretical research, or models constructed by machine learning algorithms, it is important to understand that models represent learning. In this paper, we have defined learning not as the accumulation of information, but the improvement of performance (activity) based on past experience as well. Accordingly, it should be understood that:

a) Effective learning cannot occur if the Digital Twin is not well-coupled to the people and processes that can make use of the learning that the Digital Twin has accumulated;

b) Effective information sharing requires not just raw data access, but semantic interoperability — "knowing" (whether as a human or an algorithm) what the information means;

c) Learning should be understood as ongoing, not one-time, when the real modeled system or its environment are changing;

d) Semantic interoperability of information systems is not just an information technology problem. As learning advances, entirely new domain ontologies emerge with their own new (often unpredictable until encountered) phenomena. These new ontologies carry their own new semantics, and drive new requirements for interoperability. Perhaps surprisingly, maintaining semantic interoperability is likewise an ongoing group learning activity.

e) This paper has noted that the subject of this learning is not limited to System 1 (a manufactured product, modeled by System 2), but also includes System 2 (methods of engineering and other life cycle management processes, modeled by System 3).

5.2 Recommendations on Future Steps

Consistent with the recommendation from the seminal AIAA/AIA Digital Twin Position Paper [1] and validated by the foundational work here, the Aerospace Industry recommends creating and/or leveraging an existing Aerospace Digital Transformation Consortium (ADTC) that will champion and coordinate implementation and consistency management efforts across Industry, Academia and Government in accordance with the following five objectives:

- Provide Focus (Tactical) – Working closely with Industry, the ADTC will need to prioritize how, when and where to 'focus on value' for the greatest impact while accounting for risk and cost. This is critical to ensure that implementation efforts stay focused on outcomes and business benefits. Focus should not be on Digital Twin technology itself or attempting to achieve the perfect digital enterprise/system before getting started.
- Ensure Scalability (Strategic) – Leveraging existing enterprise frameworks and models, the ADTC will own the development of a joint grand strategy and scalable framework to coordinate the Aerospace Industry efforts toward value realization from Digital Twin implementation. This is critical to ensure that tactical "learn by doing" pathfinders or pilots do not end up being one-off stunts/pilots, but are designed to integrate learning back into the broader enterprise implementation plan.

- Promote Awareness (Marketing) – Through liaising with existing consortia and professional networks, the ADTC will champion the development of a communication plan and realization of dissemination mechanisms to educate the broader community about the opportunity for value realization going forward. This is critical to raise awareness, promote adoption and coordinate collaboration across other efforts doing similar / aligned things for complementary, not competitive efforts.
- Influence Policy and Regulation (Political) – To accelerate value realization from recently published "Digital Engineering" vision and strategy documents [33, 34], an ADTC will work with Government to establish appropriate policy, regulation and incentives for top-down transformation. This is critical to connect the Executive Offices (CEO-Industry & PEO-Gov't) with the grass roots efforts underway to realize the transformation.
- Workforce Development (Education) – To promote awareness of tools and technology availability, an ADTC will work with Universities, Trade Schools, Community Colleges and other professional societies to both identify and deliver needed enhancements and development activities, dissemination of lessons learned, strategic workforce development, and sustainment needs.

To offer more context on each of the above, specific activities and next steps should be taken as part of a potential ADTC effort, as outlined below.

1. Provide Focus (e.g., how, when and where should the focus be to deliver greatest value?)

Prioritized tactical recommendations for ADTC realization are as follows:

- Define and launch appropriately scoped pathfinders – Recognizing that the opportunity space is vast and the digital enterprise landscape is complex, the Aerospace Industry recommends a tactical 'learn by doing' approach toward implementation. Recommend starting with an appropriate set of technical focus areas to: 1) clearly define and align on the problem and opportunity to be addressed, 2) formulate tangible Industry/government prioritized 'pathfinder' efforts, and 3) highlight gaps and opportunities for where a Digital Twin ADTC could help beyond the organizations and consortia that exist today. Initially, this is being pursued as a series of Technical Interchange Meetings (TIMs) with Industry, Government and Academia to establish boundary conditions for what it is, and is not. Though there are many potential focus areas, initial focus areas for the initial suite of TIMs include:
  - o Joint All Domain Command and Control (JADC2)
  - o Condition-Based Maintenance Plus (CBM+) for Sustainment
  - o Unmanned Arial Systems (UAS) / Low Cost Attritable Aircraft Technology (LCAAT)
  - o Agility Prime
  - o Certification by Analysis & Intelligent Test
  - o Aerospace & Defense Supply Chain Ecosystem
  - o … and several others.
- Accelerate Digital Inspection Adoption (linking the physical twin to its virtual representation) – The Digital Thread is a key enabler for realizing a Digital Twin. To accelerate Digital Twin value realization, the ADTC could help drive a focus on realizing tactical digital inspection solutions for cross-supply chain consumption as a broader digital thread implementation strategy is pursued. This would include standardizing approaches for consuming multiple types of digital inspection to capture "as-built" and "as-used" conditions of parts throughout the life cycle. To improve quality, better information on parts manufactured across the supply chain is critical. However, a solution must be instantiated that enables access to this information while respecting cyber security as well as appropriately respecting and valuing supply chain intellectual property attached with this information

2. Ensure Scalability (e.g., how to get multiple organizations, processes, systems, and twins to talk together for broader benefit realization?)

   Prioritized strategic recommendations for ADTC realization are as follows:

- Realize Consistency Management for Digital Engineering: This document has asserted and demonstrated the importance of establishing an appropriate enterprise framework and generic reference model for facilitating consistency management & integration across the broader Digital Enterprise. In particular, defining the boundary of the system elements that collectively form the "digital thread system" that enable Digital Twins requires a non-trivial level of care and formality to ensure scalability. As multiple Digital Twins interact and update with their connected physical assets (along with the associated models and data) the issue of consistency management becomes a central concern. This highlights another key function for any proposed ADTC, specifically to ensure the consistency management of the information flow across the broader digital enterprise.

- Establish Trust in Models and Use of Models: Use of physical test and product life cycle data to enhance the capability of the modeling and simulation tools over time will further help develop model trust, reduce physical testing requirements, and build model reliance. While some of the Digital Twin case studies reviewed in this paper were careful to pay attention to the issue of model credibility, some did not or were silent on the issue. As Digital Twins are used increasingly to inform decisions, more attention is needed on the issue of model credibility of the virtual twin in context with its intended use. This is relevant to model VVUQ (Verification, Validation & Uncertainty Quantification) as well as the 'certification/qualification/accreditation' of the personnel using the Digital Twin, the Digital Twin itself, and the use of the Digital Twin. Several organizations are making significant progress in the development of VVUQ best practice (e.g., ASME and NAFEMS). Any established ADTC should leverage strategic partnerships with these organizations to help the quality management of the digital ecosystem.
- Promote Digital Standardization – Several organizations are seeking to establish digital and data interoperability standards (e.g., AIA, ASME, SAE, NAFEMS, NIST, ISO, etc.). Rather than focus on standards, it is proposed that an ADTC would focus on establishing, articulating, demonstrating and standardizing best practices versus standards themselves. An ADTC will purpose to collaborate with other ecosystem partners to inform/develop standards based on these best practices as and where appropriate. As a specific example of digital standardization, Industry and Government need to drive the tool suppliers to provide "non-vendor specific" digital models that fully translate across systems. Most tools don't provide a perfect translation of the information. There are scalability and interoperability advantages to moving the Industry toward a "CAx system neutral model." To this end, another ADTC focus area should be on developing feature robust formats (e.g., hdf5 file like) for consistent and interoperable sharing of modeling and simulation assets which provide the foundation for the virtual representation element of a Digital Twin. In addition, an ADTC would also promote better standards and standardization for modeling and simulations so that Industry can consume and exchange simulations with suppliers, customers, and partners. This will require Customer involvement as well to promote a move toward standardized interoperable model formats.

3. Promote Awareness (e.g., how does Industry know about and align with the value realization plan?)

   Prioritized marketing recommendations for an ADTC realization are as follows:

- Facilitate Cross-Consortium Collaboration – Formulation and execution of the appropriate ADTC will leverage feedback and expertise from several existing Academia, Industry and Government championed efforts. Efforts should proceed with purposeful awareness and engagement across other Professional Societies to ensure best practice is leveraged and communicated across other societies/fields (e.g., automotive, biomedical, etc.) where appropriate. Many consortia are already partially leveraging Digital Twin capability for islands of benefit, but not in a way that exploits a broader industrial base collaboration. An ADTC would help champion Aerospace Industry collaboration across these entities for better coordination and accelerated realization of broader benefits.
- Benchmark and Publicize Benefits – The Digital Twin ADTC will operate as a curator and trusted source for vetted/trusted value cases on Digital Twin. By capturing & collating these in one place, the ADTC would provide a location where Industry is able to review validated business benefits resulting from the use of Digital Twin capabilities.

4. Influence Policy & Regulation (e.g., how does Government align to & incentivize top-down realization of value?)

   Prioritized political recommendations for ADTC realization are as follows:

- Inform Creation of Smart Policy & Regulation: To facilitate top-down alignment, an ADTC will provide guidance for government procurement policy and investment based on a common view of value and gap assessments identified from activities above. Encouraging Government, Industry, and Academic engagements for technology represents an important National Industrial Policy that an ADTC would promote. In addition, developing policy needs to also respect the protection of Intellectual Property between government, industry, and academia needs revision to support and improve effective enterprise collaboration. This is critical for aligning executive suite engagement with Digital Twin data life cycle and Digital Thread capability so as to fully realize the promised value from Digital Transformation efforts more broadly. In a heavily regulated industry, smart policy, regulation & requirements are needed to incentivize and kick-start participation across the broader Aerospace Industrial Ecosystem.

- Facilitate Realization of Digital Airworthiness Certification – As the DoD and United States Government (USG) usher in a new digital reality, better access to and utilization of data as well as the automation of tasks and processes leading to airworthiness certification are key opportunity areas. Broad industry feedback suggests the true benefit for a Digital Twin is ultimately manifested through its use to reduce physical testing and improve decision confidence (risk reduction) and tractability. However, there are many challenges with this including acceptance from regulatory authorities. Leveraging ongoing work in the areas of Certification by Analysis (CbA) and intelligent test, an ADTC will work with existing USG, DoD and Industry groups to advocate appropriate policy and regulation updates required to progress value realization from the use of Digital Twins as part of the airworthiness certification process.

5. Workforce Development (e.g., how does one measure tool maturity? How do we ensure the workforce has the proper skills to execute digital transformation?)

   Prioritized education recommendations for ADTC realization are as follows:

- Focus Tools & Methods Development – Industry feedback from the suite of TIM will identify gaps in tool maturity and methodology that need focused investment to mature. Examples from the AIAA / AIA Position Paper [1] include, but are not limited to: multi-scale, 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. In particular, the formation of an appropriate ADTC would better integrate the government, academia and industry in a consortium dedicated to the development of advanced, multi-order modeling and simulation tools, especially high-fidelity models, that can reduce physical testing and improve development speed for both hardware and software.
- Establish Digital Maturity Model and Assessment – Several Industry, Government and Academic organizations are each pursuing their respective views on how to best assess and track supply chain maturity for Digital Engineering capability. To help align the myriad of different assessment tools and approaches, an ADTC would help by 1) baselining critical features that measure maturity and 2) producing a supply chain maturity assessment tool and process for a more Industry standard approach. Similar to the development of Technical Readiness Levels and Manufacturing Readiness Levels, the development of an appropriate "Digital Engineering Desk Book" (i.e., Digital Engineering Readiness Level) would provide the context & address the need to establish level of supply chain maturity for "Digital Engineering" (which includes Digital Twin).
- Leverage Competitions & Grand Challenges – Significant success has been seen in the use of grand challenges and competitions to tackle important problems related to energy, health, education, the environment, national security, and global development. Furthermore, Academia has successfully leveraged Grand Challenge projects [35] as a means to accelerate development & foster innovation in students. An ADTC may leverage a similar approach to define a "North Star" Digital Twin challenge for collaboration between the public and private sectors.

6 Toward Implementation of Recommendations

The recommendations above highlight current gaps that the establishment of an Aerospace Digital Transformation Consortium (ADTC) could help address. However, to take the first step on the journey to realizing an appropriate ADTC, it is necessary to identify an appropriate grand challenge big enough that it cannot be delivered by one organization, but focused enough to allow Industry alignment around the problem. Of the five areas identified as potential pathfinders, Industry has identified JADC2 as an ideal candidate to take forward as an initial grand challenge or "North Star" effort.

Joint All Domain Command & Control (JADC2): The proposed pathfinder for progressing Digital Twin implementation with connection to the associated digital thread(s) or tapestry.

The need exists to develop a generic reference model for multi-domain C2 serving as input for a 'Grand Strategy' to visualize multi-domain battle operations [36]. Joint Forces used to enjoy freedom of action in the air, land, maritime, space and cyberspace domains (US Army). However, the pace of technology accelerated availability of military knowledge allowing potential adversaries the opportunity to close the technological gap denying or disrupting friendly forces' in the air, maritime, space and cyberspace domains from extended distances [36].

The DoD has expressed interest in using the joint AIAA/AIA Digital Twin Position Paper (link here) recommendations as a basis for future pilot projects exploring multi-domain integration, using an appropriate Consortium (ADTC) as the vehicle for that exploration. This requires an industry 'core team' tasked with defining the ADTC use case and charter with broad acknowledgment that requires full digital engineering scope beyond Digital Twins (i.e., the further implementation of digital thread).

Multi-domain battle management has been, or is being, explored in DoD projects (i.e., JADC2, MDC2, ABMS, Convergence, Overmatch, AB2, STO Mosaic Warfare, Overboost, etc.). The generic reference model supporting the Grand Strategy dynamically encompasses the complexities of the modern battlefield affecting rate of change in terms of information access and decisions. Battlefield visualization is enabled by principal elements, sometimes referenced as key features, such as rapid decision-making, situational awareness (SA), and the ability to direct forces. Assisting visualization through common networks, tools, and knowledge products are underlying technological enablers.

The goal of the Grand Strategy is the ability to analyze an expanded battlespace where domains can quantify operational challenges such as echelonment, speed and reach [36]. Some key interfaces include intergovernmental, Joint Service, and coalition capability integration across all military operations. A future generic reference model covers all information, processes, and automation existing between identified domains.

An ADTC, through the use of a generic reference model, will enable joint C2 for a common mission thread. In addition, a generic reference model spans a consistent set of multiple configurations and viewpoints in the form of information models, logical models, standardized frameworks, and meta-models. Furthermore, an ADTC can help provide focus and influence a resulting roadmap to accelerate benefit realization from joint C2 in an appropriately phased approach.

The breadth of the JADC2 landscape is vast, so to help scope the launch efforts, initial focus will lock in on a subset of relevant use cases. A brief vignette of one such use case scenario is provided below.

Example JADC2 Digital Twin Vignette – Digital Twins for Future Wargames

As the battlefield increases in complexity, strategic fluidity and rapid change become critical. For years, wargames have filled the gap; however, large-scale wargaming exercises require lengthy planning timelines and are costly to execute. Additionally, warfighters are hesitant to use real-world equipment and digital systems out of concerns for unintentional impacts on real-world missions. As realized by US DoD Missile Defense Agency, Digital Twins of these systems (physical and digital) can step in and facilitate the at-scale assessment of everything from vehicle configurations to the evaluation of new tactics and strategies for an infinite number of future conflict scenarios—all done digitally. Digital Twins would allow for the fusion/integration of multi-fidelity data sources, providing both situational awareness and predictive capabilities at both system and system-of-systems levels; all in a secure environment with no impact on real-world missions. When coupled with an AI/ML engine, such capability would allow for data-informed recommendations and decision making in a dynamic, multi-agent context, and accelerate the rate of change on force structure, doctrine, tactics, and warfighting equipment.

From a Digital Twin development and implementation perspective, such capability could help evaluate a number of research questions regarding the impact that:

- Model fidelity/resolution and accuracy,
- Data update frequency between physical and virtual assets,
- Latency in communications, and
- Incomplete information/data

have on both the quality of decision making and the robustness of mission strategies for any number of engagement scenarios (bottom-up approach). Inversely, desired mission outcomes could help derive requirements for Digital Twins of physical assets in terms of necessary model fidelity, data quality and transfer rate, etc. (top-down approach).

7 Concluding Remarks

Today, many individual organizations are realizing targeted benefits from using Digital Twins and Digital Engineering capabilities within their businesses. To amplify the realization and value of Digital Twins more broadly, this paper presented the INCOSE ASELCM Ecosystem reference model as a means to describe how Digital Twins integrate with the broader digital enterprise. It also introduced real-world examples of aerospace Digital Twin use cases and discussed how the generic reference model supports the various use case applications. However, more extensive benefit realization through integration across the broader enterprise will not happen without the purposeful creation of a new, trusted, and multi-domain entity that serves the function of consistency manager across the Aerospace Enterprise. To this end, the Aerospace Industry advocates:

- Creation of appropriate Aerospace Digital Transformation Consortium/Consortia (ADTC) to address this identified need, and
- JADC2 as an initial pathfinder focus area to use as an ADTC's inaugural effort.

Now is the time to accelerate the Aerospace Industry benefits from this transformative capability … together.

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10 Appendices

10.1 Appendix A – Glossary of Terms and Abbreviations

ABMS
Advanced Battle Management System

ADTC
Aerospace Digital Transformation Consortium

AIA
Aerospace Industries Association

AIAA
American Institute of Aeronautics and Astronautics

API
Application Programming Interface

ASDL
Aerospace Systems Design Laboratory

ASELCM
Agile Systems Engineering Life Cycle Management. The ASELCM Pattern is a reference model used to describe, analyze, or plan innovation ecosystems. It has been used to study innovation process agility, group learning, managed trust, adaptive ecosystems, digital engineering, Digital Twins, and digital threads.

ASME
American Society of Mechanical Engineers

CAF
Credibility Assessment Framework

CbA
Certification by Analysis

Consistency Management Role
The business process role(s) responsible for managing various consistencies across the life cycle of a managed system. This includes inspection of managed information to evaluate consistencies or inconsistencies, and to reconcile then. Examples of such consistency management roles include managing the consistency of system Digital Twins (model-based simulations) with real systems; the consistency of system designs with system requirements; the consistency of stakeholder needs with system requirements; the consistency of system design with system production; the consistency of system requirements and design with in-service utilization; the consistency of system models with architectural frameworks, ontologies, and standards; and many other consistencies across the life cycle of a managed system.

C2
Command & Control

DEIC
Digital Engineering Integration Committee

Deployed Generic Model (Pattern)
Information representing past experience in learning about a managed system, for current and future use in related situations. Used to generate Specific Models for current or future projects. The Generic Model may be a formal, configurable, reusable model-based pattern subject to digital curation; or informal knowledge accumulated by human experts; or intermediate levels of formalization. The "deployed" term refers to the fact that the generic pattern has been subject to previous validation, uncertainty quantification, and, credibility assessment, sufficient for it to be deployed for future use. The generic pattern is also subject to formal description by a Metadata Descriptor.

DoD
Department of Defense

EASA
European Union Aviation Safety Agency

Engineered System
Any system of interest that is subject to research and development, engineering, production, distribution, deployment, utilization, sustainment, and retirement. Includes manufactured products as well as service offerings.

Engineering and Life Cycle Management Processes
The activities that manage the life cycle of (System 1) Engineered Products. Includes R&D, Engineering, Production, Distribution, Deployment, Operation, Sustainment, and Retirement. This includes both learning new things about System 1 and its environment, and applying that knowledge to improve System 1.

FAA
Federal Aviation Administration

FEA
Finite Element Analysis

FEMAP
Finite Element Modeling and Postprocessing

GT
Georgia Tech

ICME
Integrated Computational Materials Engineering

ILFI
International Living Futures Institute

INCOSE
International Council on Systems Engineering. See also www.incose.org

Innovation Ecosystem
The environment with which System 2 interacts across its own life cycle. It includes the life cycle management system responsible to plan, deploy, and evolve the System 2 life cycle management system. System 3 is responsible to observe and learn about System 2 and its environment, not just plan and deploy it. The planning and deployment of a Digital Twin for System 1 is a responsibility of System 3.

Interface
An Interface is an association of a (1) a System, which presents the Interface; (2) a set of Input-Outputs, which pass through the Interface; (3) a set of Interactions, which describe behavior at the Interface; and (4) a System of Access (SOA), which provides the medium that enables and characterizes details of the Interface.

IP
Intellectual Property

ISO
International Organization for Standardization

ISS
International Space Station

IT
Information technology

JADC2
Joint All Domain Command and Control

KBISD
Kendeda Building for Innovative Sustainable Design

Learning & Knowledge Manager for Life Cycle Managers of Target Systems
The subset of Engineering and Life Cycle Management Processes that is responsible for learning new things about System 2 and its environment. This is the learning (not application) part of R&D, Engineering, Production, Distribution, Deployment, Operation, Sustainment, and Retirement of System 1.

Learning & Knowledge Manager for Target Systems
The subset of Engineering and Life Cycle Management Processes that is responsible for learning new things about System 1 and its environment. This is the learning (not application) part of R&D, Engineering, Production, Distribution, Deployment, Operation, Sustainment, and Retirement of System 1.

Life Cycle
For an Engineered System, a series of stages through which it progresses, from early concept through realization by design and production, to deployment, operations, support, enhancement, and retirement. These stages include various aspects of life cycle management, managing consistencies across transitions between life cycle stages.

Life Cycle Domain System
The Life Cycle Domain System, which is the environment with which the Engineered System interacts across its life cycle. This includes all the Life Cycle Management systems responsible for the Engineered System (engineering, manufacturing, distribution, operations, sustainment, etc.). System 2 is responsible to observe and learn about System 1 and its environment, not just engineer and deploy it. A Digital Twin for System 1 is a subsystem of System 2, which also includes the users of that Digital Twin.

Life Cycle Manager of Life Cycle Managers
The subset of Process Life Cycle Management Processes that is responsible for applying what has already been learned to the management of the life cycle of System 2. This is the application (not learning) art of Engineering, Production, Distribution, Deployment, Operation, Sustainment, and Retirement of System 2.

Life Cycle Manager of Target System
The subset of Engineering and Life Cycle Management Processes that is responsible for applying what has already been learned to the management of the life cycle of System 1. This is the application (not learning) part of Engineering, Production, Distribution, Deployment, Operation, Sustainment, and Retirement of System 1.

Managed Digital Twin System Boundary
The system scope that includes information (Specific Model, Observed or Generated Datasets and Artifacts, Deployed Generic Pattern, and Metadata) and process (Consistency Management Roles) sufficient to provide Digital Twin information services whose consistency with a real system is managed to achieve trusted consistency. Refer to Figure 8.

MDC2
Multi-Domain Command and Control

Metadata (Descriptor)
The information which describes a Model, Pattern, or Dataset. This may include specification of what the subject model, pattern, or dataset itself describes; its intended uses; the provenance (origin) of that information; various indications of validation, verification, uncertainty quantification, credibility assessment, or other credibilities; the scope, type and nature of the described model, pattern, or dataset; applicable languages; semantic aspects; related artifacts; maintenance and curation information, and other aspects. Such metadata is conceptually a

"wrapper" for the described model, pattern, or dataset, in the sense of the wrappers and labeling found on retail product wrappers or packages. The metadata enhances ability to share or exchange models, patterns, and datasets.

MBSE
Model-Based Systems Engineering

M&S
Modeling & Simulation

NAFEMS
International Association for the Engineering Modelling, Analysis and Simulation

NASA
National Aeronautics and Space Administration

NASMAT
NASA Multiscale Analysis Tool

NIST
National Institute of Standards and Technology

Observed or Generated Datasets and Artifacts
A collection of managed information that may originate from empirical observations of a System 1 Engineered System (as in service or in a test rig), or its Environment; it may also originate as the output of a digital simulation (as in a Digital Twin or otherwise) provided by a Specific Model; it may also originate as information collected as Stakeholder Inputs, so that those three cases cover (1) empirical observation, (2) past validated knowledge, or (3) Stakeholder inputs; it may also include generated artifacts such as machine generated or more traditional documents. The observed or generated dataset or artifact is also subject to formal description by a Metadata Descriptor.

OMG®
The Object Management Group, a consensus standards consortium publishing standards for information technologies that include the Systems Modeling Language (SysML).

OT
Operational Technology

PCM
Pressurized Cargo Module

Process Life Cycle Management Processes
The activities that manage the life cycle of (System 2) processes of R&D, Engineering, Production, Distribution, Deployment, Operation, Sustainment, and Retirement of (System 1) Engineered Systems. For example, activities that change processes for product engineering, production, or maintenance.

RCAS
Rotorcraft Comprehensive Analysis System

SAE
Society of Automotive Engineers

SE
Systems Engineering

Specific Model
Structured information describing an Engineered System or its Environment. Examples include digital MBSE models, executable simulations that include physics-based models or data-driven models (as in the case of machine learning models), or other forms of structured models. More broadly, structured data such as mechanical part prints, schematic diagrams, architectural drawings, bills of material, or other data structures may be considered Specific Models. The "specific" term refers to the concept that such a model may have been configured or derived, in part or whole, from a generic Pattern, for a particular use--and is therefore more "specific." The specific model is also subject to formal description by a Metadata Descriptor.

Stakeholder Features of System 2
System 2 includes the Engineering and Life Cycle Management Processes responsible for management of System 1, the Engineered Product. Different instances of System 2 will have different capabilities. Those capabilities are the Stakeholder Features of System 2, representing various capabilities to perform aspects of engineering, production, sustainment, and other life cycle management processes. The complete library of System 2 Stakeholder Features describes a configurable reference list of capabilities that includes those found in ISO 15288, the INCOSE SE Handbook, Agile Systems Engineering, and other reference models. In the ASELCM Reference Pattern, the capabilities of a System 2 of interest are "configured" by configuring its Stakeholder Features. Refer to Figure 4

STO
DARPA's Strategic Technology Office

SysML®
The Systems Modeling Language, specified by the SysML Partners collaboration of OMG.

System 1 (The Engineered System)
Any system of interest that is subject to research and development, engineering, production, distribution, deployment, utilization, sustainment, and retirement. Includes manufactured products as well as service offerings.

System 1 Stakeholder Advocate An organizational role responsible for representing and advocating to the business on behalf of the stakeholders of System 1, the Engineered System. May be filled by multiple specialists across different types of stakeholders and stakeholder concerns.

System 2 (The Life Cycle Domain System)
The environment with which the Engineered System interacts across its life cycle. This includes all the Life Cycle Management systems responsible for the Engineered System (engineering, manufacturing, distribution, operations, sustainment, etc.). System 2 is responsible to observe and learn about System 1 and its environment, not just engineer and deploy it. A Digital Twin for System 1 is a subsystem of System 2, which also includes the users of that Digital Twin.

System 3 (The Innovation Ecosystem)
The environment with which System 2 interacts across its own life cycle. It includes the life cycle management system responsible to plan, deploy, and evolve the System 2 life cycle management system. System 3 is responsible to observe and learn about System 2 and its environment, not just plan and deploy it. The planning and deployment of a Digital Twin for System 1 is a responsibility of System 3.

System Life Cycle Business Process
One of the multiple business processes of an enterprise, supply chain, or larger business ecosystem concerned with the life cycle management of System 1. Versions of these include the processes of ISO 15288, the INCOSE Systems Engineering Handbook, DoD 5000, or enterprise-specific business processes covering management of any part of the entire life cycle of System 1.

System of Access (SOA)
A System of Access is a system providing a medium for interaction between system components, through Interfaces. Examples of SOAs include data networks, sensors, actuators, hydraulic connections, mechanical or structural linkages, user interfaces, application programming interfaces (APIs), the Internet, postal mail, the telephone system, atmospheric transmission of sound, biological enervation, or other media.

TIM
Technical Interchange Meeting

Trusted Model Repository
One of a set of information systems relied upon to provide information of known credibility. This means that both the information provided by this information system, as well as the information system itself, are both trusted by their users. The Trusted Model Repository(ies) provide access to Specific Models, Generic Patterns, Datasets, and the Metadata describing them.

USG
United States Government

VVUQ
Verification, Validation and Uncertainty Quantification

2CES
2nd Century Enterprise Systems

10.2 Appendix B – Case Studies

10.2.1 Cygnus Orbital Ferry Vehicle Digital Twin

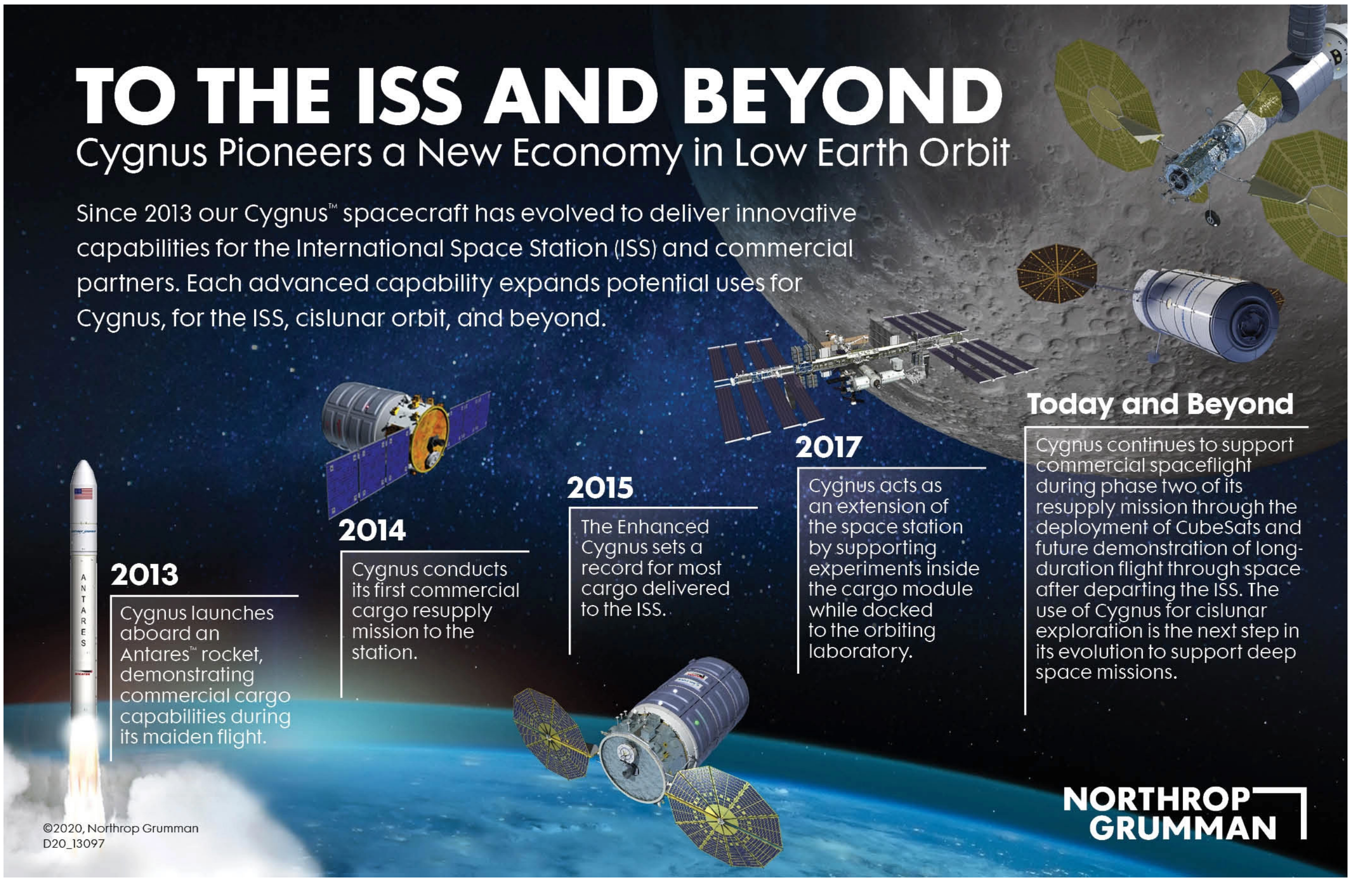
The Cygnus Spacecraft is a flight proven design incorporating elements drawn from Northrop Grumman and its partners' existing, flight-proven spacecraft technologies. Cygnus carries NASA cargo to the ISS and provides all spacecraft functions necessary for safe rendezvous, berthing, unberthing, final descent and reentry. It is used to carry crew supplies, spare equipment and scientific experiments to the space station. The Cygnus spacecraft is composed of two main elements the Service Module and the Pressurized Cargo Module. The Service Module incorporates advanced avionics developed by Northrop Grumman and guidance and navigation components that allow for fully autonomous rendezvous with the space station. It provides all of the utility services to the cargo modules, manages the autonomous rendezvous to the ISS, provides requires resources to allow the mission to be successfully completed, has a structural interface to the launch vehicle and cargo modules, and is integrated at Northrop Grumman's facility.
The Pressurized Cargo Module (PCM) provides a pressurized, thermally benign environment for NASA cargo. It can support powered payloads, supplying up to 150 Watts of electrical power and thermal conditioning to active payloads. The PCM is built in Thales Alenia's manufacturing facility in Turin, Italy. In addition to the standard pressurized cargo delivery services, custom services are offered for cargo items that require power, cooling, specialized mounting or handling requirements. Disposal of refuse or otherwise expendable hardware from ISS is also provided, typically equal in mass to at least the amount of cargo delivered on any single mission. The avionics design fully meets all of the demanding NASA safety

requirements imposed on human-rated vehicles [37].

The Cygnus vehicle missions change from mission to mission. The Northrop Cygnus team utilizes Digital Twins for the Service Module. For example, propellant usage during a mission is an important parameter where pre-mission results are compared with actual performance data. When the spacecraft is close to ISS rendezvous, there is certain checkpoint information that is reported back to NASA; that information updates predictions based on validated Digital Twin pre-launch tools. While stopped in orbit longer than predicted impacts missions, real-time updates are predicted based on the Service Module Digital Twins, that include not only propellant usage, but include Guidance Navigation and Control (GNC) pre-launch predictions. GNC simulations are continuously update from actual Cygnus flight sensors. These updates and comparisons to the predicted performance are important because there is a segment of the mission (~4 hours before ISS rendezvous) that the Cygnus spacecraft goes into an autonomous mode where the Commercial Resupply Services (CRS) does its own maneuvers based on internally received sensor information and ISS information. Cygnus reports in advance to NASA and Northrop what maneuvers it will perform autonomously, and those maneuvers are compared with pre-launch predictions. The only reserved command during this mission segment is 'STOP' to prevent collisions due to differences between predicted and actual performance.

The Cygnus vehicle provides a number of advanced capabilities during cargo resupply missions. The spacecraft has already demonstrated a number of these, including the launch of cube satellites from external deployers, the delivery of live rodents to the station, the ability to act as a laboratory space while docked to the station, boosting the station's orbit and flying in orbit separately from the station for more than one year [38].

Currently, Northrop Grumman uses Cygnus to perform ISS resupply flights under the second CRS contract. Beginning in 2014, Cygnus has carried more than 70,000 pounds (31,500 kg) of critical cargo to the station under the first CRS-1 contract. In November 2019, the company flew the first CRS-2 mission, NG-12, and will carry out a minimum of five additional missions under this contract [38] (Figure 13).



TO THE ISS AND BEYOND

Cygnus Pioneers a New Economy in Low Earth Orbit

Since 2013 our Cygnus™ spacecraft has evolved to deliver innovative capabilities for the International Space Station (ISS) and commercial partners. Each advanced capability expands potential uses for Cygnus, for the ISS, cislunar orbit, and beyond.

2013

Cygnus launches aboard an Antares™ rocket, demonstrating commercial cargo capabilities during its maiden flight.

2014

Cygnus conducts its first commercial cargo resupply mission to the station.

2015

The Enhanced Cygnus sets a record for most cargo delivered to the ISS.

2017

Cygnus acts as an extension of the space station by supporting experiments inside the cargo module while docked to the orbiting laboratory.

Today and Beyond

Cygnus continues to support commercial spaceflight during phase two of its resupply mission through the deployment of CubeSats and future demonstration of long-duration flight through space after departing the ISS. The use of Cygnus for cislunar exploration is the next step in its evolution to support deep space missions.

Figure 13. To the ISS and Beyond [38]

10.2.2 ICME Optimization of Advanced Composite Components of the Aurora D8 Aircraft

The objective of this research is to develop an integrated approach to design and optimize the composite Y-joints and composite acreage panels used in the Aurora D8 aircraft. This objective will be achieved by linking material models, structural models, and experiments at multiple length scales. Emphasis will be given to understanding the tie between product design and composite manufacturing. Specifically, the manufacturing-microstructure correlation and its effect across the higher length scales will be established through atomistically-informed process modeling simulations embedded into Finite Element (FE) micromechanics models. Virtually-cured micromechanics models will be linked to meso- and macroscale models using respectively the NASA software NASMAT and HyperSizer. NASMAT will be used to study the fabric materials used in the Y-joint and to determine strength allowables. Information will be passed across the length scales synergistically (hierarchical in space and concurrent in time) to optimize structural components at the macroscale using the structural optimization code HyperSizer. Results from each scale will be used to modify the cure cycle, toughen specific regions of the model, and selectively modify the composite layup. This aeronautical relevant benchmark problem will serve to demonstrate the benefits of the ICME (Integrated Computational Materials Engineering) approach as shown in Figure 14.

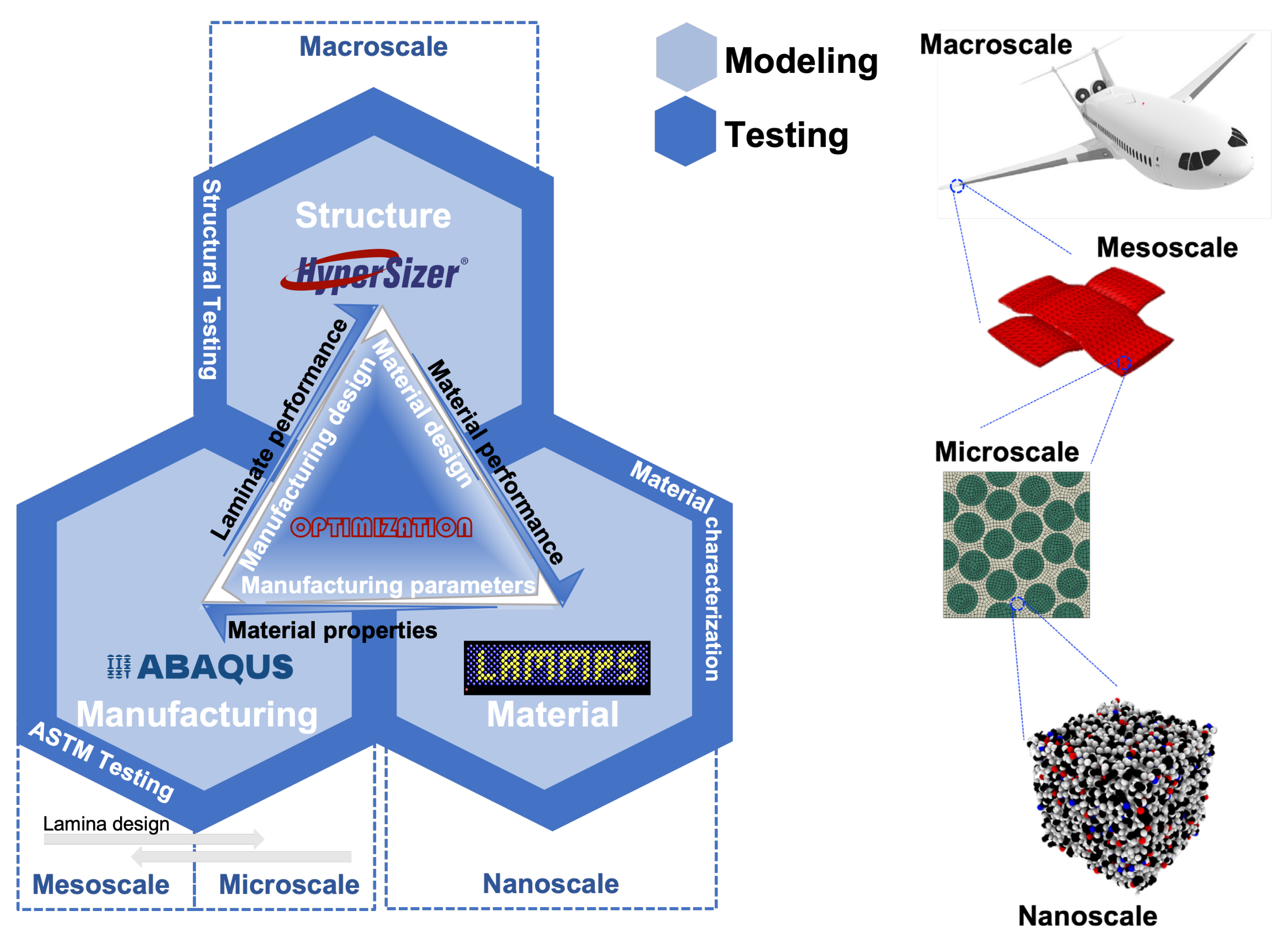


Figure 14. Proposed ICME approach

Digital representative models will be generated at every scale including the atomistic, microscale, mesoscale and macroscale and integrated as in Figure 15. These digital models may or may not constitute a Digital Twin depending upon the degree to which each representation agree with scale dependent metrics of merit associated with physically measurable material quantities still to be established. The work is organized in four fully coupled tasks as shown in Figure 15.

At the nanoscale (Task 1), a molecular dynamic (MD) model of the crosslinked polymer will constitute the Digital Twin of the bulk resin material during curing. The inputs at this scale include resin and hardener chemical structure, nanoparticle type, and curing temperature. The outcome of this task will be the full MD characterization of the thermo-mechanical properties (mass density, cure shrinkage, elastic properties, strength, coefficient of thermal expansion and glass transition temperature) of the resin during curing for input into Task 2.

The digital representations of the composite at the microscale (Task 2) will be generated through finite element (or alternatively NASMAT) and subjected to virtual curing and virtual testing. The "Digital Twin(s)" will account for random fiber distribution across the composite tows. Inputs at this scale are properties of the matrix as a function of crosslinking density from Task 1, fiber properties, fiber volume fraction, and processing parameters. The outputs of this task, including residual stress and ply-allowables, will serve as the inputs for Task 3.

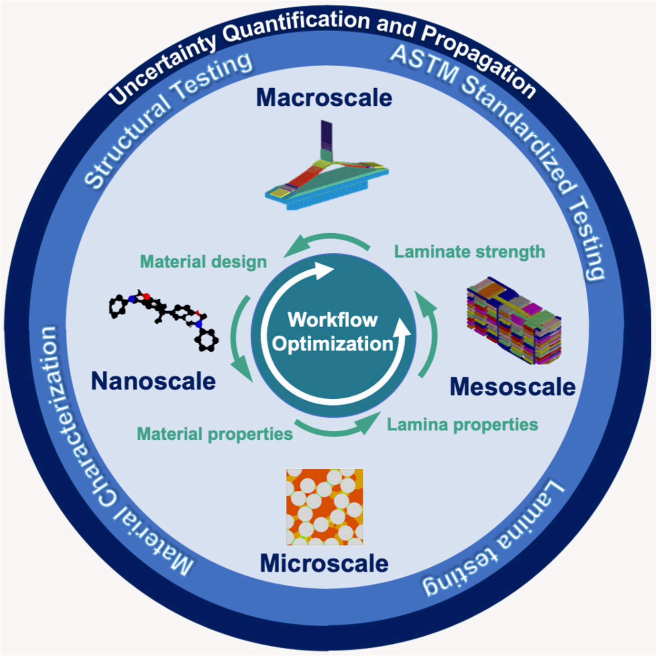


Figure 15. ICME approach including, Digital Twins and inputs/outputs at every scale for the "design with the material" paradigm

At the mesoscale (task 3) the digital representation of the textile composite will be virtually recreated using NASMAT. This "Digital Twin(s)" will allow the team to study the sensitivity of the material to manufacturing-induced imperfections, including voids, fiber misalignment, and microcracks, as shown in Figure 16.

A Digital Twin of the Y-joint (a subscale macroscale model) will be generated in HyperSizer to optimize the final joint configuration during Task 4. Inputs required to conduct analyses and sizing of the laminates and textile structures are the lamina elastic moduli as a function of curing (axial, transverse, shear), lamina stress and strain (axial, transverse, shear) allowable values, and lamina thickness and density, all of which come from Task 3. In HyperSizer these values are used in conjunction with user-selected strength, stiffness, and stability criteria as well as manufacturing constraints. The latter often include rules relating to minimum percentage of plies in each orientation (e.g., 0, 45, -45, 90 degrees) as well as symmetry of laminates. The primary outputs of the analysis and sizing for use in Task 4 are optimal cross-sections (geometry and lamination) for each laminate type considered (tapes or fabrics), corresponding margins of safety for each criterion selected, computed mass, and strengths in all directions including peeling. Tapes will be optimized using HyperSizer, textiles will be analyzed through high-fidelity RVEs and lower-fidelity NASMAT models.

A macroscale Digital Twin of the Y-joint and surrounding acreage panels will be recreated in FEMAP and HyperSizer to determine the optimum cost/performance trade-off for the D8 Y-joints and connected composite panels. The primary inputs for this task are the material properties and mesoscale allowables from Task 3. Input/output (I/O) from each scale will constitute the digital thread of this ICME framework, as shown in Figure 16. Data and metadata at each scale (i.e., digital thread) will be stored and tracked to perform sensitivity studies and to highlight potential implementation issues within the ICME platform.

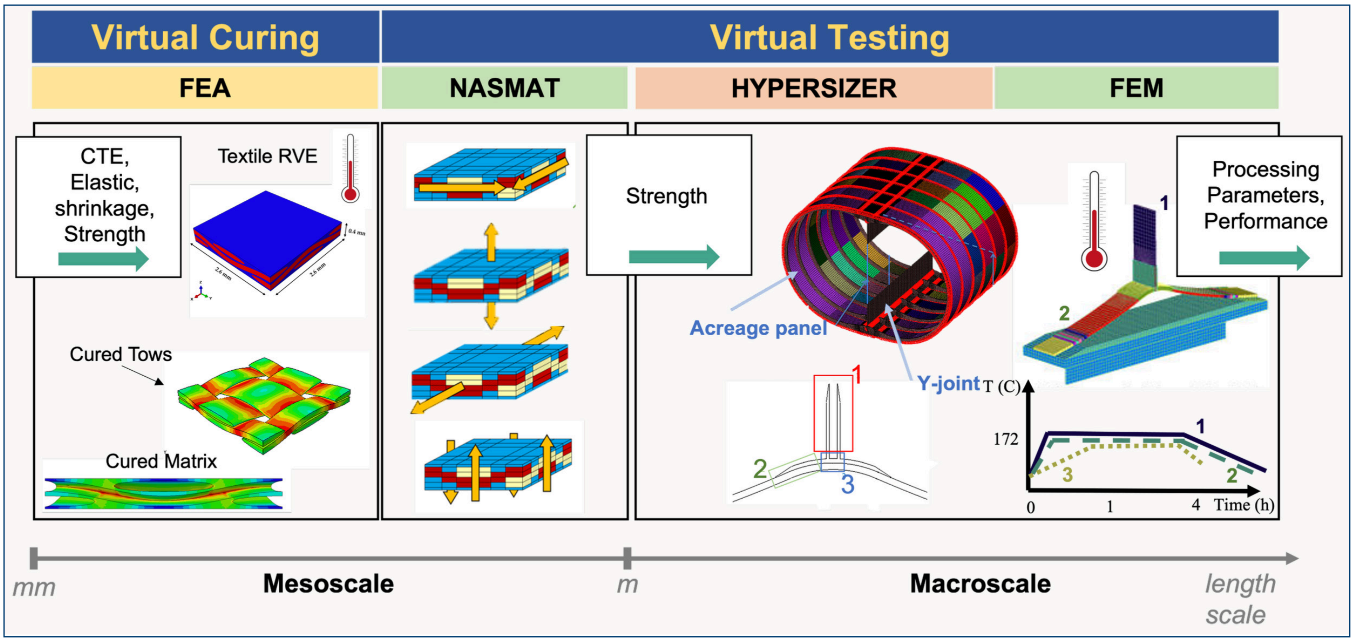


Figure 16: Virtual testing tools for ICME and I/O exchange across the meso and macro-scales

10.2.3 Rotorcraft Component Digital Twin

Rotorcraft components experience different stress levels based on the flight parameters and intensity of the mission, which in turn dictates the maintenance schedule as well as remaining useful life of the component. In order to improve the resilience of a rotorcraft in safely completing a mission, the rotorcraft's maneuvers can be designed or modified to minimize the stress experienced by critical mechanical components. We developed a component stress-aware rotorcraft flight parameter optimization methodology by building a Digital Twin for the component of interest. The Digital Twin fuses the information from sensor data, probabilistic diagnosis, probabilistic prognosis, and enables selection of maneuvers that minimize the stress in the critical component. Comprehensive rotorcraft analysis and finite element models are used to predict the stress in the rotorcraft component under different flight conditions. Sensor data is used to estimate the health state and calibrate the prognosis model error after every flight. Surrogate models are constructed for diagnosis and prognosis to increase the efficiency of the uncertainty and optimization analyses. The flight parameters are optimized for a future mission using the estimated health state and/or the updated prognosis model. The Digital Twin methodology is demonstrated with a synthetic experiment for a simple flight path.

10.2.3.1 Digital Twin Purpose and Use

Rotorcraft components experience degradation due to repeated use in intensive missions, environmental loads, and general wear and tear, causing an increase in the frequency of maintenance operations and reduction in performance reliability. If the stress level experienced by a component during a mission is reduced, significant extension of a component's operation before the next maintenance can be achieved, thus facilitating longer missions. One way to reduce the stress experienced by a component is to select the maneuvers and flight parameters that minimize the stress experienced by the component of interest, while satisfying the mission requirements. Rotorcraft can especially benefit from flight path and maneuver optimization since a helicopter has multiple maneuver options during flight covering all six degrees of freedom. However, such an optimization methodology needs to know the current state of the system through diagnostic measurements and the predicted states of the system during a desired future mission through a prognostic model. In addition, both the diagnostic information and prognostic models contain aleatory and epistemic uncertainty that needs to be accounted for in the optimization. The Digital Twin concept is suitable for developing such a methodology, since the Digital Twin is a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems. Building and updating Digital Twins of critical rotorcraft components or for the entire rotorcraft will thus greatly help fleet management, maintenance, mission planning, and mission execution.

The Digital Twin paradigm pursued here uses rotorcraft-specific models for inference and operational or maintenance schedule optimization. That is, the variability in loads/stresses experienced by components in different rotorcraft in the fleet, due to their flying history and other sources of variability will be considered for making rotorcraft-specific operational or maintenance decisions. The Digital Twin-based decision-making process thus advances the state of the art in two different aspects: a) use individual rotorcraft-specific analysis and information for decision making, and b) support proactive operational decisions such as maneuver optimization, in addition to reactive decisions like maintenance and repair.

10.2.3.2 Rotorcraft Maintenance and Flight Planning: The State of the Art and Challenges

Presently, health and usage monitoring systems (HUMS) are used for making decisions regarding condition-based maintenance of rotorcraft. HUMS include on-board sensors (accelerometers, magnetic sensors, etc.) and data storage equipment. The data recorded by sensors is downloaded and analyzed to recognize regimes flown by the rotorcraft. The loads experienced by critical components for different regimes are (assumed to be) known based on separate experiments performed on a chosen rotorcraft from the fleet. In this manner, the trio of HUMS, regime recognition, and regime-load experimentation on a representative rotorcraft establish the utilization metric (e.g., fatigue life) of a component, and help in performing condition-based maintenance. The condition-based maintenance process is thus only approximately related to the degradation actually experienced by the specific, individual rotorcraft. Variability in manufacturing of rotorcraft components, measurement errors in HUMS, model errors in regime recognition, and modeling and measurement errors in regime-load experimentation contribute to the prescription of potentially dangerous or uneconomical maintenance scheduling of rotorcrafts. Rotorcraft mission planning, on the other hand, currently does not include rigorous consideration of an individual rotorcraft's current health state or previous flying history. A well-maintained rotorcraft is assumed to be able to fly all maneuvers specified by the manufacturer. Fleet operators and pilots may use their judgement and heuristics to tailor a flight plan, but a systematic framework for component health- or stress-aware flight planning of a particular individual rotorcraft is not available at present.

A digital-twin-based operational optimization scheme is an attractive option for intelligent maintenance and flight planning for an individual rotorcraft. In such a scheme, a probabilistic prognosis model is used to predict the quantity of interest such as stress or crack growth, given a set of candidate operational options. Building an updating such a probabilistic prognosis model is a challenging information fusion-related task. The prognosis model consists of rotorcraft analysis that couples aerodynamics and stress analyses in order to predict the stress resulting from a future flight profile, given the current state of the rotorcraft. The high-fidelity physics models used for prognosis include Rotorcraft Comprehensive Analysis System (RCAS) software and a stress analysis (finite element) software. RCAS also uses the finite element method for resolving aero-structural dynamics equations of the entire vehicle, but in order to perform higher fidelity (three-dimensional) stress analysis on a component, a separate finite element software (e.g., ABAQUS) was used. Since the optimization algorithm needs stress prediction during each iteration, computationally inexpensive surrogate models that enable the estimation of stresses given the flight parameters were constructed and employed in the optimization. These surrogate models also introduce surrogate model errors that were included in the prognosis and optimization. The discrepancy between the prognosis surrogate models and reality needs to be calibrated using noisy sensor data, collected during rotorcraft flight. In addition, the prognosis model could also include the up-to-date knowledge regarding the health state of the component. This involves collecting (diagnostic) sensor data, building a diagnostic forward model, and solving the inverse problem to perform health diagnosis. The main tasks in building a useful, probabilistic prognosis model include: a) generating training data using computational physics models (RCAS, FEA, etc.) to train sufficiently accurate prognostic and diagnostic surrogate models, b) surrogate model form selection and surrogate model training, c) sensor data collection, d) prognosis discrepancy estimation, and e) component health diagnosis. The results of diagnosis are used to update the prognosis model, which is used in optimizing the flight profile and maneuvers in the next mission, while

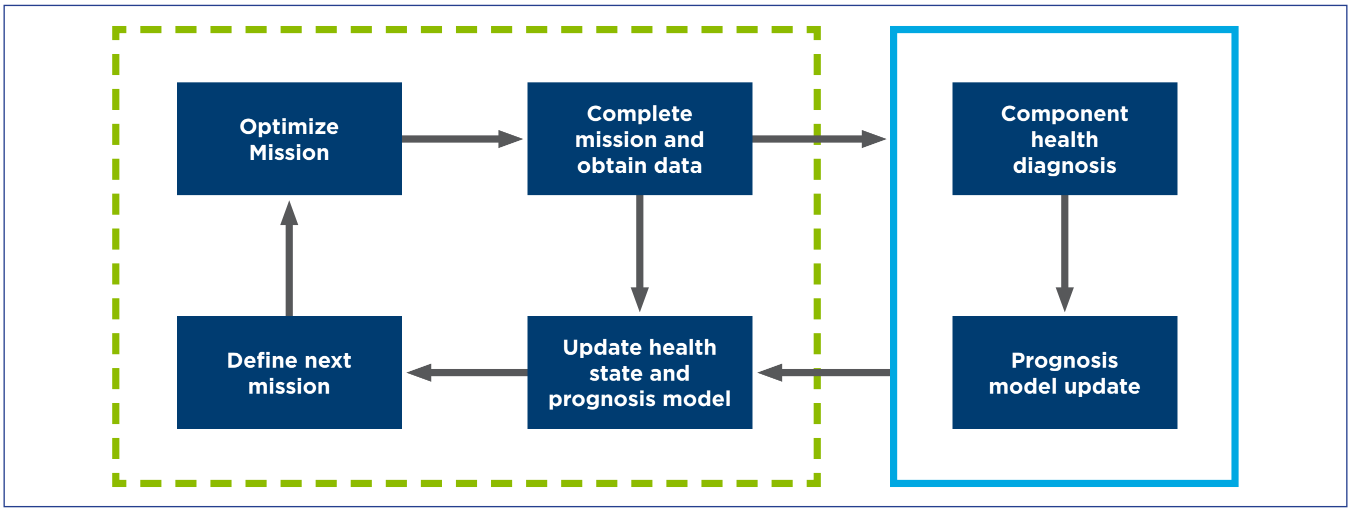


Figure 17. Digital twin for stress-aware rotorcraft flight planning

incorporating uncertainty in the model, sensor data, and future mission characteristics.

10.2.3.3 Digital Twin for Stress-Aware Rotorcraft Flight Planning

The three key elements of the proposed Digital Twin-based methodology are given by: a) development of a probabilistic prognosis model, b) utilization of sensor data to update the health state of the component as well as the prognosis model, and c) flight parameter optimization under uncertainty for a given future mission. In order to minimize the stress on the component of interest, a probabilistic prognosis model must be constructed, and the diagnostic information must be used to update the prognosis model (see Figure 17).

The goal of the proposed maneuver design methodology is to minimize the stress experienced by a chosen component in the system (rotorcraft mast); details are available in [39]. Different parameters that define maneuvers of a rotorcraft (linear or angular velocities or accelerations) could be used to define the intensity of a maneuver as well as the degree of stress experienced by the component. Acceleration of the rotorcraft could be used to quantify the intensity of a maneuver as it represents the net effect of external forces acting on the rotorcraft. However, the rotorcraft may fly with zero or near-zero accelerations for long periods of time. Hence, we use the rotorcraft's linear velocity to indicate maneuver intensity. Note that as acceleration and velocity are related, velocities indirectly represent the net effect of external forces applied on the rotorcraft. The stress experienced by the component thus depends on the loading, which in turn depends on rotorcraft's kinematic state described by its velocity, and the health state of the component. In order to design rotorcraft flight parameters that minimize the stress experienced by the component of interest, the prognosis model needs to be able to estimate the stress history experienced by the component for the given set of velocities of the rotorcraft and the damage state. The damage state, like a reduction in the cross-sectional area in a small region, is estimated using strain measurements and probabilistic diagnosis. The information obtained from sensor data is provided to the prognosis model to enable component-specific prognosis for the quantity of interest. In the present case, sensor data is needed for a) estimating the state of degradation (or health) of the component, and b) estimating the discrepancy in the prognosis model. In the first case, we consider that the component of interest progressively degrades during the life of the rotorcraft, depending on how the component is used. Given sensor data, diagnosis methods can be used to track the damage state of the component at the beginning/end of a mission. Secondly, we recognize that the prognosis model is only an approximate representation of reality, and needs to be corrected by using a model discrepancy term. We assume a model form for this discrepancy term, and calibrate this discrepancy model using sensor data. Note that the updated knowledge regarding the health state is considered in decision-making through the prognosis model. Hence, if diagnosis is not performed, the prognosis model error due to the erroneous knowledge regarding the health state of the system may get assimilated into the overall prognosis model correction term.

This may provide a sufficiently accurate, corrected prognosis model. However, sometimes it is important to know the health state of the system regardless of its impact on the operational decision-making, in order to support sustainment decisions (i.e., maintenance or repair). Hence, in this work we explored the two aforementioned alternatives of assimilating system-specific information into the Digital Twin.

10.2.4 Manufacturing Digital Twin Framework

Digital twins can enable more accurate and more timely modeling of manufacturing results. More accurate results enable better measurements which can be used to improve the form, fit and function of a product. More timely results allow for processes to be adjusted before they are completed, which reduces costs [40] .

Modeling Digital Twins during manufacturing is challenging because the processes that must be measured were developed over many years. In many cases they will have been optimized several times to make them as efficient as possible. Adding Digital Twins is only beneficial if further savings can be made without reducing quality or slowing production.

The ISO 23247 Digital twin framework for manufacturing has been developed to help industry make Digital Twins during manufacturing [41]. The framework is defined as a specialization of the ISO 30141 Internet of Things reference architecture, and describes how to combine data standards to make digital representations for Digital Twins.

Multiple data standards are necessary because, at least for the moment, no single standard can define a complete representation of a manufacturing Digital Twin. For example, to make Digital Twins of machined parts, the STEP standards can be used to capture data about the design and planning, the MTConnect standards can be used to capture data about the machining results, and the QIF standards can be used to capture data about the inspection results. In principle, STEP can be extended to include modeling of manufacturing results, but its internal technology is less well suited to fast processing than the technology adopted by MTConnect.

We describe the ISO 23247 standard and how it can be used to make Digital Twins. Three case studies were developed to test the standard. The paper gives details for the first case study in which a team of robots were assigned the task of drilling and filling holes on a wing assembly. The deployment of Digital Twinning made the robot team more flexible because last minute changes could be made to the production plans.

10.2.4.1 Challenges of Manufacturing Digital Twins

There are multiple challenges to making Digital Twins during manufacturing.

- There are real time requirements that must be met for the data to be captured and processed in time to make adjustments to the manufacturing process.
- There are precision requirements that must be met if the twins are to add value to existing methods.
- There are modeling requirements that must be met if the twins are to be a detailed representation of the manufactured items.

Today no single standard or system is able to meet all of these challenges. For example, CAD/CAM systems are able to model all of the data necessary to describe a manufactured part, but they cannot capture manufacturing results in real time. Similarly, machine control systems are able to operate in real time, but they only model the toolpaths that must be run to create the contours of the part. Lastly inspection systems are able to evaluate the final geometry of a part with great accuracy, but they do not capture the full life cycle of the part.

Furthermore, in order to perform its function each system adopts the best technology for its use case. Therefore, CAD/CAM systems use data structures that are very extensible, CNC stream their data into very large files that can be analyzed later, and inspection systems use data structures that are easily adapted to new use cases. To make an accurate, detailed model of the Digital Twin in a timely fashion these capabilities need to be combined in a way that does not negate the key capability of each technology.

Figure 18 shows how the ISO 23247 framework does this by dividing the manufacturing space into four levels represented as entities in the architecture of the Internet of Things as described by ISO 30141. The lowest level contains Observable Manufacturing Elements (OME). These are the things that are to be modeled as Digital Twins. They are the physical devices and products on the shop floor. They are also the manufacturing processes whose operations can be observed on the manufacturing floor.

The second level is the Device Communication Entity (DCE). This entity records the state of the OME. There are many kinds of OME's, and many kinds of sensors that can be used to capture their state changes. The Device Control Entity aggregates the signals from these sensors into time stamped data streams.

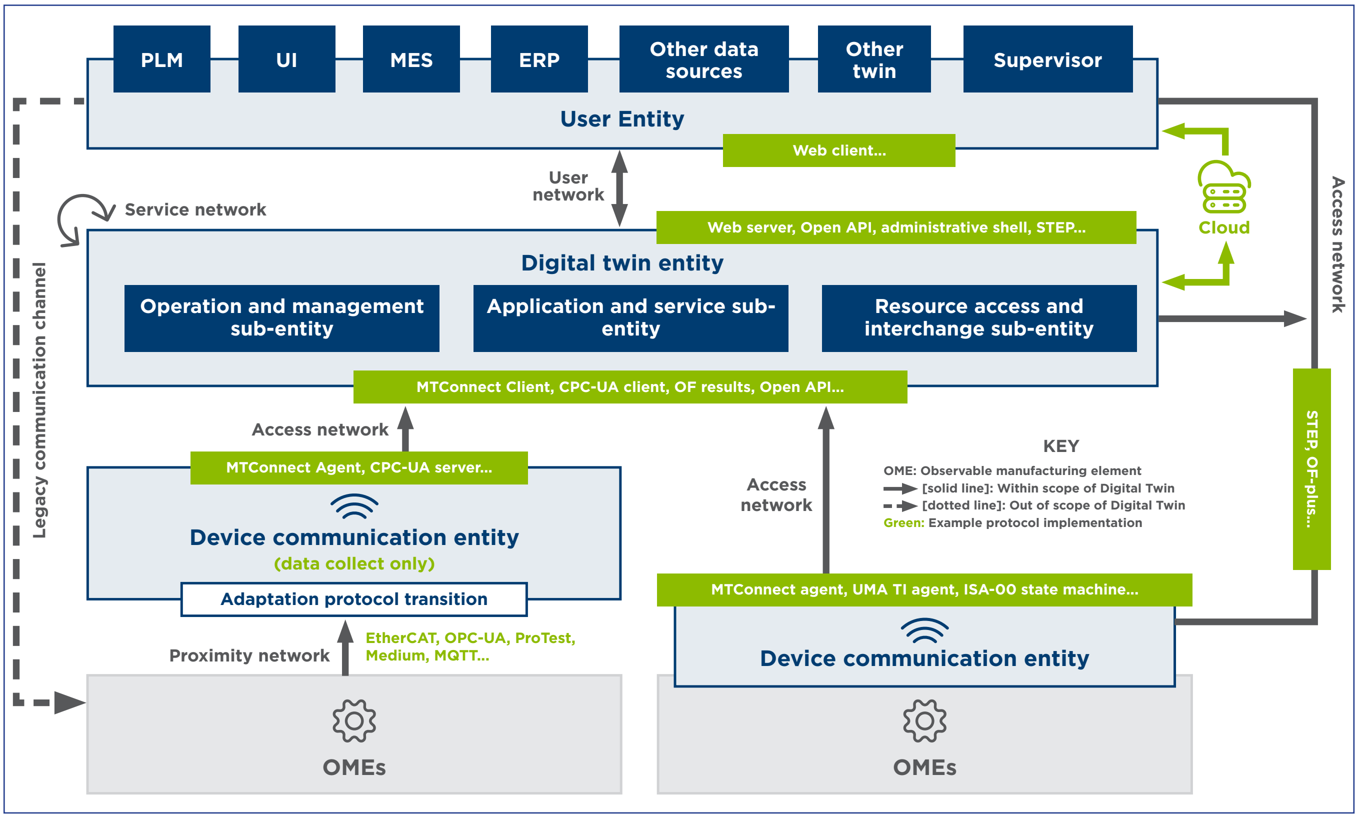


Figure 18. Digital Twin Manufacturing Entities

The third level is the Digital Twin Entity (DTE). This is the core entity of the architecture. The DTE models the OME's by processing the data streams created by the DCE. At the start of a manufacturing session, the DTE is seeded with CAD models of products, and CAM models of processes. These models are then changed using simulation during the manufacturing in response to events recorded by the DCE. For example, material may be removed from a CAD model of a block in response to the motions of a cutter.

The fourth level is the User Entity. This entity contains the applications that want to use the information in the Digital Twins. They may be traditional applications such as a PLM or an MES, or they may be new applications such as a robot planning application that determines which operations must be run for a particular configuration of a wing.

10.2.4.2 Three Case Studies

In the summer of 2020, three case studies were implemented to validate the Digital Twin framework

4. A robot teaming case study in which multiple robots were used to drill and fill holes for an airframe wing
5. A hole stack-up case study in which a wing is divided into composite, titanium and aluminum layers.
6. A machine monitoring case study in which a feed override is activated, and impacted tolerances are detected and validated.

All three test cases were developed to show how Digital Twinning can make manufacturing more flexible and accurate.

Figure 19 shows a manufacturing cell at a laboratory in the University of Washington. This cell was used as test bed for the first study. There are four robots called Kenny, Kyle, Cartman and Stan. Like in the SouthPark show, Kenny dies before the end of most production runs.

In the first case study, the framework was used to enable last minute changes to the manufacturing plan. These changes included a robot becoming unavailable because of a malfunction, a feature being unnecessary because of a difference in a wing configuration, and an operation being performed at an earlier stage of the manufacturing. For these cases, Digital Twin models of the wing, robot and drilling process allowed planning software to determine the best response to the changes.

Figure 19. Robot Manufacturing Cell at the University of Washington

The second case study measured the thickness of multiple disks in a stack. Each disk represented one of the layers on the wing. Multiple stacks were made to represent the wing at different locations where holes were to be drilled and filled. Each disk was measured using a caliper and its depth was sent to a CAD modeler for analysis. The stack-up for all the disks was calibrated and a best fit depth for the fastener was computed. Figure 20 shows the disks and calipers.

In practice there are small differences in the thickness of the composite layer of a wing because of variations in the layup and curing process. Therefore, the hole stack-up can vary when the composite layer is attached to the titanium frame via an aluminum shim. Traditionally, this has been managed by determining a maximum size for the stack-up. The fasteners are then required to have sufficient length for this stack-up. However, in the average case this means there is excess material on the fastener and for the thousands of holes on a typical airframe this small addition can add up to hundreds of pounds of excess weight.

The second use case showed that Digital Twinning can be used to capture the actual size of each stack-up in the airframe. The fastener size is then trimmed to this size, or to the closest size defined for a family of already cut fasteners. The fastener is then delivered to the person or robot performing the assembly. The Digital Twin model enables the operators and regulators to verify that the fastener length is correct for each of the instances.

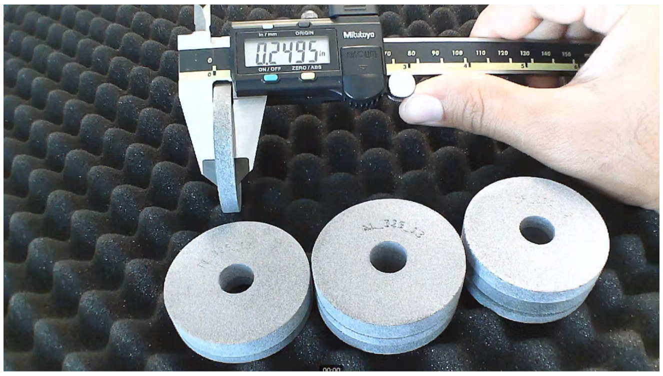


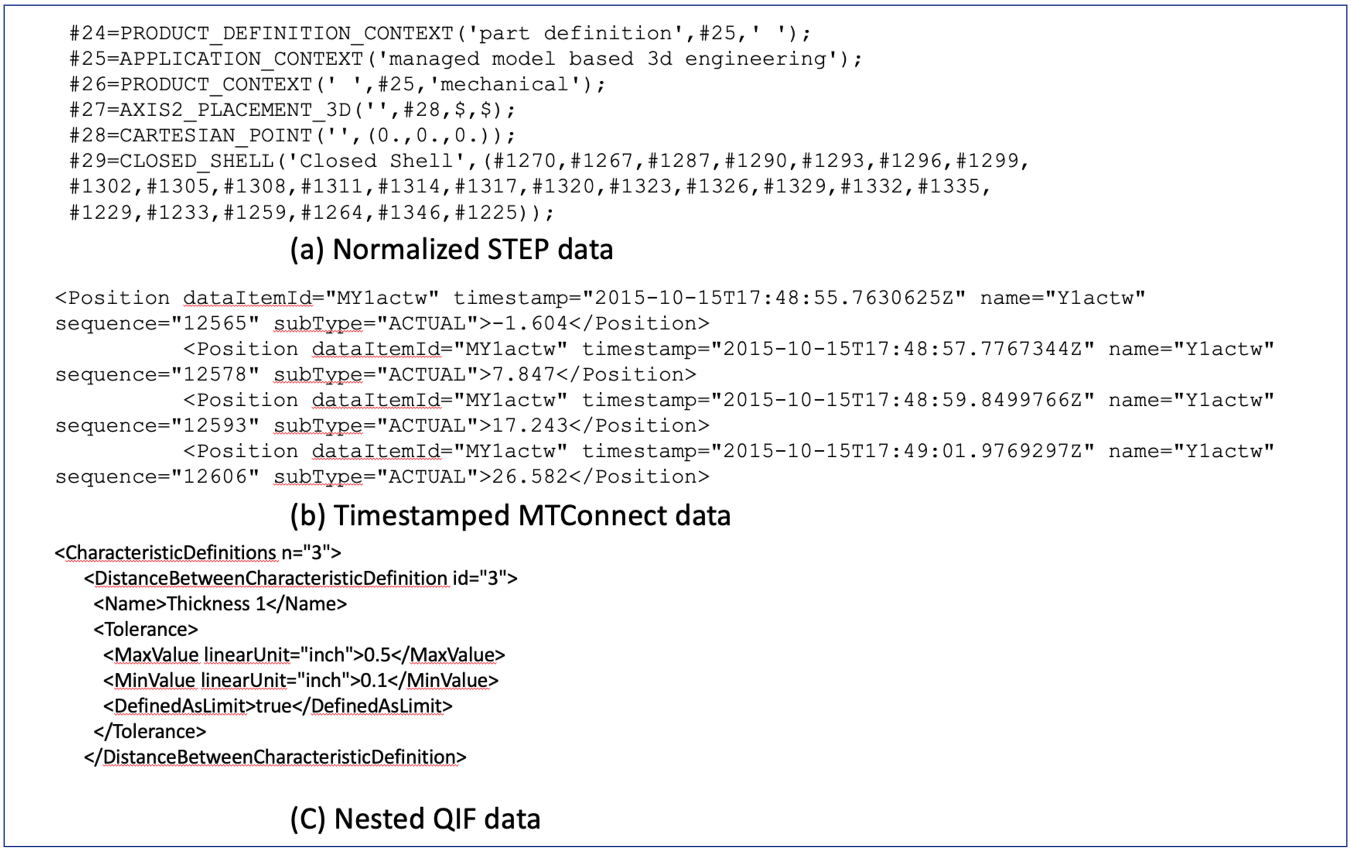
Figure 20. Disk stacks measured for second test case

The third case study monitored the machining of a high precision gear box. The critical dimensions of the features were analyzed to determine if any exceptions occurred during their machining. If one was detected, then the dimension in question was analyzed for subsequent measurement on a CMM machine.

In the third use case, operator time is saved by only checking the tolerances that may have been impacted by a change in the machining conditions. In this case the as-planned machining program, which is assumed to be correct, is compared to the as-executed machining plan captured in the MTConnect. Where discrepancies are found, an analysis is done to determine what faces where being machined at the time of the change, and if those faces have a tolerance they are flagged for checking on a CMM.

The three case studies all used STEP AP242 to model their design data [3], STEP AP238 to model their manufacturing processes [42], MTConnect to capture their machining results [43] and QIF to capture their inspection results [44]. As previously mentioned, STEP has been engineered to enable upward compatibility as new capabilities are added to CAD and CAM models. MTConnect has been engineered to quickly capture and stream machining results, and QIF has been engineered to measure many different kinds of products. As a result, STEP uses a highly normalized data structure, MTConnect has a flat easy to write structure and QIF has an easy to customize nested XML structure.

Figure 21 shows three data fragments from the three standards. The STEP data is normalized so it is divided into entities that only reference each other when there is a dependency in the information. For example, a closed shell is required to reference its faces. The



```
#24=PRODUCT_DEFINITION_CONTEXT('part definition',#25,' ');
#25=APPLICATION_CONTEXT('managed model based 3d engineering');
#26=PRODUCT_CONTEXT(' ',#25,'mechanical');
#27=AXIS2_PLACEMENT_3D('',#28,$,$);
#28=CARTESIAN_POINT('',(0.,0.,0.));
#29=CLOSED_SHELL('Closed Shell',(#1270,#1267,#1287,#1290,#1293,#1296,#1299,
#1302,#1305,#1308,#1311,#1314,#1317,#1320,#1323,#1326,#1329,#1332,#1335,
#1229,#1233,#1259,#1264,#1346,#1225));
```

(a) Normalized STEP data

```
<Position dataItemId="MY1actw" timestamp="2015-10-15T17:48:55.7630625Z" name="Y1actw"
sequence="12565" subType="ACTUAL">-1.604</Position>
          <Position dataItemId="MY1actw" timestamp="2015-10-15T17:48:57.7767344Z" name="Y1actw"
sequence="12578" subType="ACTUAL">7.847</Position>
          <Position dataItemId="MY1actw" timestamp="2015-10-15T17:48:59.8499766Z" name="Y1actw"
sequence="12593" subType="ACTUAL">17.243</Position>
          <Position dataItemId="MY1actw" timestamp="2015-10-15T17:49:01.9769297Z" name="Y1actw"
sequence="12606" subType="ACTUAL">26.582</Position>
```

(b) Timestamped MTConnect data

```
<CharacteristicDefinitions n="3">
   <DistanceBetweenCharacteristicDefinition id="3">
    <Name>Thickness 1</Name>
    <Tolerance>
      <MaxValue linearUnit="inch">0.5</MaxValue>
      <MinValue linearUnit="inch">0.1</MinValue>
      <DefinedAsLimit>true</DefinedAsLimit>
    </Tolerance>
   </DistanceBetweenCharacteristicDefinition>
```

(C) Nested QIF data

Figure 21. Data fragments from the three standards

MTConnect data is a sequence of flat records in XML. Each one has a time stamp and sequence number. Each one records an event that happened on a device. The QIF data is nested. Each object describes a characteristic of a product that is being measured.

10.2.4.3 The Robot Drill and Fill Case Study

To save space only one of the three case studies will be described in detail. The other three cases studies are similar. More detail on all three can be found in the appendices of ISO 23247-4.

Figure 22 shows how the framework was applied to the first case study. In this case study, four robots in a manufacturing cell were used to “drill and fill” holes onto an aircraft wing. For this use case, the manufacturing operations were described using AP238, the design constraints were described using AP242, the machining results were described using MTConnect, and the measurement results were described using QIF.

First the wing dimensions were inspected. A virtual assembly was then adjusted using the QIF measurement results. This virtual assembly informed planning software that decided which operations are to be performed by each robot. The operation list was transmitted to the robots as Gcode to drill and fill the necessary holes. This machining was monitored by an MTConnect agent to make sure there were no exceptions. The input to the process was a Digital Twin of the as-is state of the wing. The output was a Digital Twin of the new state of the wing.

The value of Digital Twinning is that it enables increased quality while reducing costs. For example, the last-minute planning implemented by the process updater of Figure 22 made the robots more productive. If a robot was not available then its work was distributed to other robots, if an operation was not necessary for this wing, then its robot was assigned other work.

The case study used STEP AP242 to represent a CAD model of the wing, STEP AP238 to represent

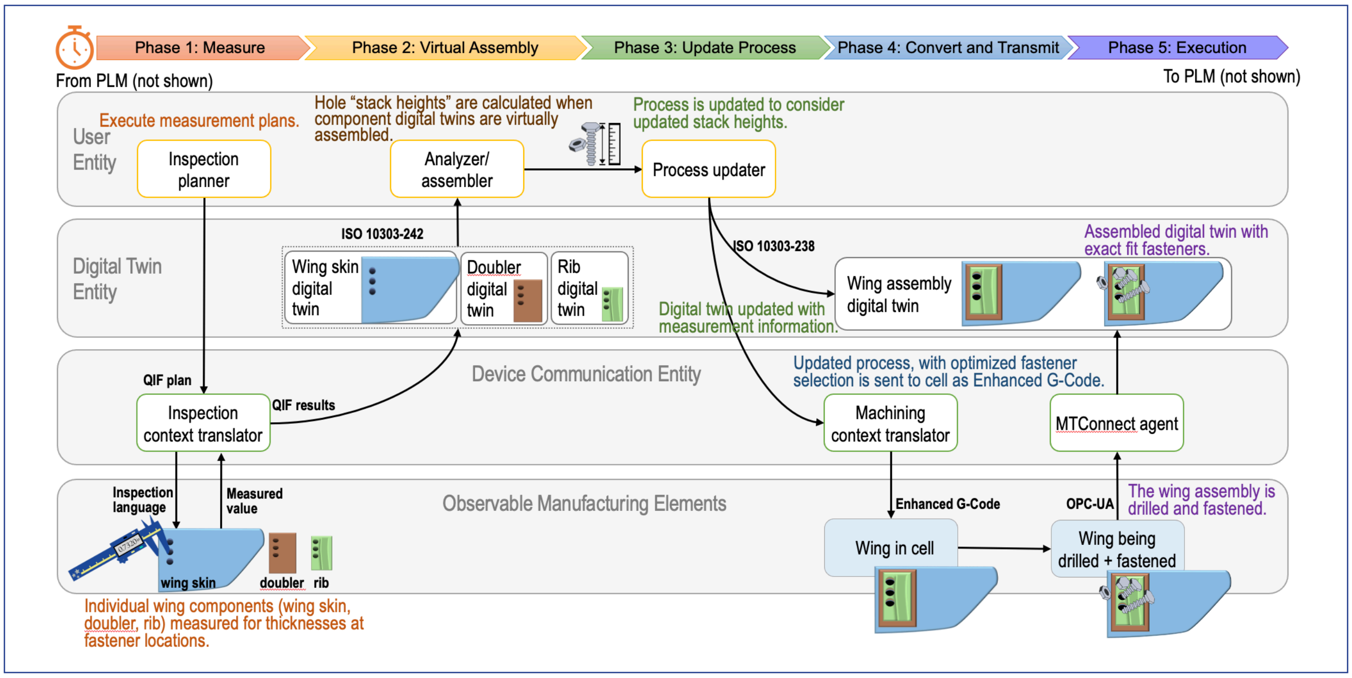


Figure 22. Digital Twin manufacturing of a wing assembly

the drill and fill process, MTConnect to represent the results of the drilling process and QIF to represent the results of QIF of inspection operations. The data was linked within the framework using Universally Unique Identifiers (UUIDs) [45].

The UUIDs were created by data translation systems. For the use case, UUIDs were assigned for the design tolerance data, the inspection planning geometry, and the machining operations. The design tolerance UUIDs were shared with a design system that is assumed to be managing its data using an AP242 file. The inspection planning UUIDs were shared with a CMM system that is assumed to be managing its data using a QIF file. The machining operation UUIDs are shared with a machining system that is assumed to be managing its data using an MTConnect file.

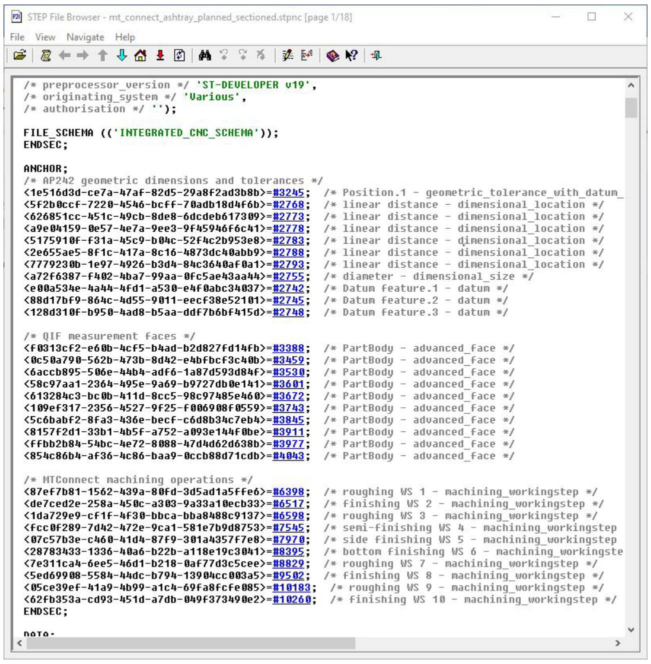
When two files describe the same twin, they are required to associate the same UUID to that twin. Each file format is allowed to manage the associations differently. Figure 23 shows how it was managed for AP238 files. A new section of the STEP Part 21 file lists the UUIDs assigned to the twins, and associates that UUID with an internal STEP entity. When an application wants to access a twin, it searches for the UUID and finds the internal entity.

The content of each file is created by a PLM system. The internal identifiers will change for each iteration of the file. The ISO 23247 framework allows this, but requires the same UUID to be assigned to the same Digital Twin for external operations. This increases the burden for the data translators. They need to store the UUID of each twin in an internal database so that they can be reused for new versions of the data. In practice this was not difficult because the translator already understands the semantics of the data. For example, the AP238 translator knew that it is creating tolerance twins for the design system, geometry twins for the inspection system and machining twins for the manufacturing system. The UUIDs for those twins are stored in the master data and reused for subsequent translations.

MTConnect and QIF use an XML format so in these cases the UUID is implemented using an attribute or element. The following code fragment shows a UUID a QIF file.

```
<DistanceBetweenCharacteristicItem id=”12”>
  <Description>Ti Nom.Thickness 3</Description>
  <Name>Thickness 3</Name>
  <CharacteristicDesignator>
    <Designator>89</Designator>
    <UUID>59e88002-1abc-416b-a3e3-
1b022248408b</UUID>
  </CharacteristicDesignator>
  <CharacteristicNominalId>11</
CharacteristicNominalId>
</DistanceBetweenCharacteristicItem>
```

Comments are added to help the IT organization understand the linking and manage the systems. This included comments to group UUIDs by system functionality, and comments to distinguish between twin instances. In Figure 23 the instance comments give the machining twins easy to understand names, but are less useful for the inspection twins because to understand geometry you need to see a visualization. In the future, new software tools may be developed to assist with this data management.



STEP File Browser - mt_connect_ashtray_planned_sectioned.stpnc [page 1/18]

```
/* preprocessor_version */ 'ST-DEVELOPER v19',
/* originating_system */ 'Various',
/* authorisation */ '');

FILE_SCHEMA (('INTEGRATED_CNC_SCHEMA'));
ENDSEC;

ANCHOR;
/* AP242 geometric dimensions and tolerances */
<1e516d3d-ce7a-47af-82d5-29a8f2ad3b8b>=#3245;  /* Position.1 - geometric_tolerance_with_datum_
<5f2b0ccf-7220-4546-bcff-70adb18d4f6b>=#2768;  /* linear distance - dimensional_location */
<626851cc-451c-49cb-8de8-6dcdeb617309>=#2773;  /* linear distance - dimensional_location */
<a9e04159-0e57-4e7a-9ee3-9f45946f6c41>=#2778;  /* linear distance - dimensional_location */
<5175910f-f31a-45c9-b04c-52f4c2b953e8>=#2783;  /* linear distance - dimensional_location */
<2e655ae5-8f1c-417a-8c16-4873dc40abb9>=#2788;  /* linear distance - dimensional_location */
<7779230b-1e97-4926-b3d4-84c3640af0a1>=#2793;  /* linear distance - dimensional_location */
<a72f6387-f402-4ba7-99aa-0fc5ae43aa44>=#2755;  /* diameter - dimensional_size */
<e00a534e-4a44-4fd1-a530-e4f0abc34037>=#2742;  /* Datum feature.1 - datum */
<88d17bf9-864c-4d55-9011-eecf38e52101>=#2745;  /* Datum feature.2 - datum */
<128d310f-b950-4ad8-b5aa-ddf7b6bf415d>=#2748;  /* Datum feature.3 - datum */

/* QIF measurement faces */
<f0313cf2-e60b-4cf5-b4ad-b2d827fd14fb>=#3388;  /* PartBody - advanced_face */
<0c50a790-562b-473b-8d42-e4bfbcf3c40b>=#3459;  /* PartBody - advanced_face */
<6accb895-506e-44b4-adf6-1a87d593d84f>=#3530;  /* PartBody - advanced_face */
<58c97aa1-2364-495e-9a69-b9727db0e141>=#3601;  /* PartBody - advanced_face */
<613284c3-bc0b-411d-8cc5-98c97485e460>=#3672;  /* PartBody - advanced_face */
<109ef317-2356-4527-9f25-f006908f0559>=#3743;  /* PartBody - advanced_face */
<5c6babf2-8fa3-436e-becf-c6d8b34c7eb4>=#3845;  /* PartBody - advanced_face */
<8157f2d1-33b1-4b5f-a752-a093e144f0be>=#3911;  /* PartBody - advanced_face */
<ffbb2b84-54bc-4e72-8088-47d4d62d638b>=#3977;  /* PartBody - advanced_face */
<854c86b4-af36-4c86-baa9-0ccb88d71cdb>=#4043;  /* PartBody - advanced_face */

/* MTConnect machining operations */
<87ef7b81-1562-439a-80fd-3d5ad1a5ffe6>=#6398;  /* roughing WS 1 - machining_workingstep */
<de7ced2e-258a-450c-a303-9a33a10ecb33>=#6517;  /* finishing WS 2 - machining_workingstep */
<1da729e9-cf1f-4f30-bbca-bba8488c9137>=#6598;  /* roughing WS 3 - machining_workingstep */
<fcc0f289-7d42-472e-9ca1-581e7b9d8753>=#7545;  /* semi-finishing WS 4 - machining_workingstep
<07c57b3e-c460-41d4-87f9-301a4357f7e8>=#7970;  /* side finishing WS 5 - machining_workingstep
<28783433-1336-40a6-b22b-a118e19c3041>=#8395;  /* bottom finishing WS 6 - machining_workingste
<7e311ca4-6ee5-46d1-b218-0af77d3c5cee>=#8829;  /* roughing WS 7 - machining_workingstep */
<5ed69908-5584-44dc-b794-13904cc003a5>=#9502;  /* finishing WS 8 - machining_workingstep */
<05ce39ef-41a9-4b99-a1c4-69fa8fcfe085>=#10183;  /* roughing WS 9 - machining_workingstep */
<62fb353a-cd93-451d-a7db-049f373490e2>=#10260;  /* finishing WS 10 - machining_workingstep */
ENDSEC;

DATA
```

Figure 23. Digital Twin UUIDs in an AP238 file

AP238, more formally known as ISO 10303-238:2020 is an information standard for describing manufacturing solutions. In its first edition, the standard defined subtractive machining programs for AP203 and AP214. In its second edition the standard defines additive and subtractive programs for AP242 Edition 2.

AP238 enables a form of manufacturing in which models are used to control processes [46]. In the late 1950's, a manufacturing paradigm was established in which codes to control a machine tool are created by a Computer Aided Manufacturing (CAM) system. The CAM operator analyses the geometry of a component and determines a series of operations that will convert an input (the stock) into an output (the workpiece). The operations are executed by moving cutting tools along paths. These paths are then converted into codes for a Computerized Numerical Control (CNC) system [47].

AP238 was used in the case studies because it allows a Digital Twin to model just-in-time changes to products, processes, and resources. For example. as a tool wears its diameter changes, or as a product is assembled its dimensions are adjusted. An application that uses AP238 to model its data can detect these changes and compare the as-planned manufacturing model to an as-measured model. The AP238 application can then generate a new machining program to meet the new conditions.

AP238 defines a language for manufacturing that divides a task into a tree of workplans containing workingsteps. Different types of workplans can be defined for programs that have optional or parallel components. Workingsteps select tooling, and define operations to machine features. For example, a workingstep may mill a pocket, or melt material to create a layer. The STEP-NC control language was developed as ISO 14649. AP238 Edition 1 mapped this language into the integrated resources of STEP so that the operations, features, and tooling of a machining solution can be linked to the product geometry and topology defined by AP203 and AP214.

AP238 Edition 2 extends the links to include the PMI, Kinematics and Tessellated models defined by AP242 Edition 2. The PMI enables checking of the dimensions of a machining result against design requirements. The kinematics means a machine tools capabilities can be validated against the motion requirements of the machining program. The tessellated models allow AP238 operations to be applied to additive manufacturing processes as well as subtractive ones. Each layer of the material is modeled as a thin mesh. Workingsteps are used to control the power and focus of the laser as it fuses material to create the topology.

AP238 was used in the three case studies to represent the process data that controlled the manufacturing. For each application, a supervisor was implemented in the User Entity to monitor the progress of the manufacturing. When the machine monitoring system detected the start of a new operation, then the supervisor was updated to the next workingstep in the program. When a tolerance was inspected by the CMM system, a dimension was updated in the product model.

The measurement system may be on the machine tool or in an external Coordinate Measurement Machine (CMM). When the monitoring system reports results that differ from the as-planned process, the supervisor uses the measurement system to check the tolerances of features that may have been impacted by the discrepancy.

For example, if the feed override is activated by an operator, then the monitoring system reports the UUID of the current workingstep using MTConnect. The supervisor can then use AP238 to determine which feature on the product model was being machined and to find any tolerances that should be validated for conformance to the AP242. The measurement system is then activated. It measures the tolerances and reports the as-measured values. The tolerances are also identified using a UUID. The supervisor relates each measured value to its PMI requirements, and requests assistance if there is potential for an issue on the final part.

10.2.4.4 Current Limitations

The framework worked well for the three case studies because the UUIDs could be generated in advance of production by the PLM translator. For the machining, they were placed into the machining Gcode by the robot supervisor, and returned to the supervisor in the MTConnect stream. For the inspection, they were placed into the inspection plan by the robot supervisor and returned to the supervisor in the QIF. As each UUID was processed the corresponding value in the AP238 file was updated. At the end of the manufacturing, the updated AP238 was returned to the PLM to describe the new state of the manufacturing.

For future versions of the framework, consideration is being given to the adoption of version 5 UUIDs. In version 5, a new UUID is generated from a seed UUID and a key value. Therefore, the same UUID can be generated for the same operation. In general, a cascade of UUIDs may be generated. Figure 23 how this might operate for a product with multiple versions, multiple instances, and multiple characteristics.

The difficulty with the UUID 5 solution is that the downstream UUIDs must change if the seed UUID changes. Therefore, when two versions of a product have the same characteristic, they have different UUIDs in each version. This negates the value of being able to detect the same Digital Twin by identifying the same UUID. In general, managing UUIDs becomes a complex problem if you want to store their history and relationships. Ongoing work is examining how to perform this management by tracking a graph of UUIDs in an information model.

The framework is also limited by the range of data that can be modeled by each standard. In the case studies, this limited the applications to the additive and subtractive machining of features that can be dimensioned using AP242. New editions of the standards are being planned for applications such as wire harness assembly and composite layup. Each will require considerable work because defining normative information models for standards is not easy.

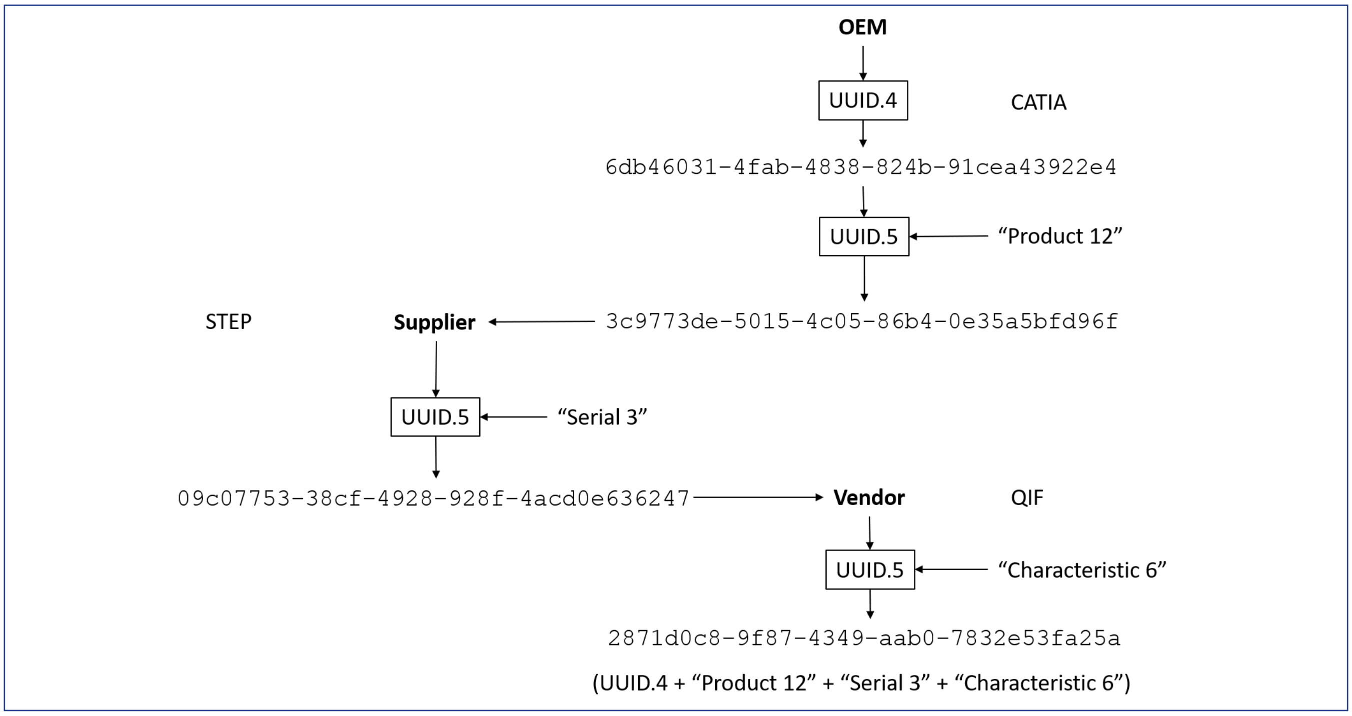


Figure 24. Tracking relationships using Version 5 UUIDs

If one extensible standard contained all the necessary data, then new standards would not be necessary. However, as previously mentioned different technologies are better suited to different requirements. Thus, STEP is good at modeling extensible information because of its normalized data structures, MTConnect is good at capturing machining results because of its timestamped data structures, and QIF is good at capturing inspection results because of its nested data structure. Using today's information technology, you cannot get all three in one solution, but it may be possible for future standards and systems.

10.2.4.5 Lessons Learned

An effective Digital Twinning solution for manufacturing needs to deploy multiple technologies. ISO 23247 defines a framework in which these technologies can co-exist. The framework is divided into entities that perform different functionalities for the modeling. The results of the functionalities are linked using Universally Unique Identifiers (UUIDs).

The deployment of UUIDs as a method to link different standards was highly effective for the three test cases tested during the summer of 2020. These test cases showed that substantial improvements can be made to the quality and reliability of manufactured products using Digital Twinning.

The first test case showed how to make a robot cell more flexible by using the Digital Twin data to change the production plan when a robot was unavailable, or an operation was unnecessary. The second test case showed how to reduce the weight of an airframe by tracking the stack-up of its composite, titanium and aluminum layers. The third test case showed how to track what faces should be measured when exceptions occur during machining.

The framework defined a common organization for the three test cases. In this organization multiple data formats were used to represent the Digital Twins. The different formats were necessary for performance and accuracy reasons. They were linked by putting the same UUID into the same Digital Twin data in each format. This worked well for applications where the Digital Twins that need to be modeled are known in advance.

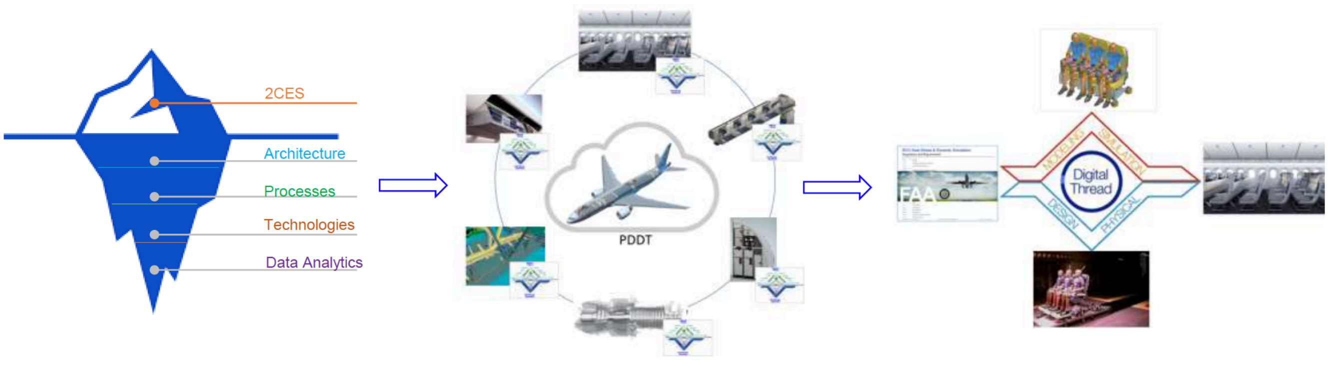
All three case studies are being considered for production deployment.

10.2.5 Smarter Seat Certification Testing Digital Twins

Passenger safety is a critical priority for Boeing commercial airplanes, and seat installations are a key aspect of passenger safety. Proven advanced analytical methods referred to as "Digital Twins" are used at Boeing throughout aircraft development, design and certification to ensure all regulatory requirements are met. While seat structural integrity and occupant safety have been historically assured through certification testing, the same level of passenger safety can be achieved by analytical methods due to recent advancement of "Digital Twin" computer modeling and simulation technology. Regulatory Advisory Circular (AC) 20-146 [48] provides the requirements and applicability of using Digital Twin towards seat Smarter Certification Test.

This use case is the result of collaboration between The Boeing Company, seat suppliers, academia, and regulatory agencies to establish standard work instructions for developing Digital Twins for seat dynamic simulation. These simulations serve to verify structural integrity and occupant safety, as well as to improve design quality and predictability. An added benefit of Digital Twins is the ability to reliably streamline certification through smarter testing. Significant effort was made to align all stakeholders and define the minimum but sufficient standard work instructions that will enable consistency in analysis methodologies across seat suppliers.

Use of Digital Twins and model-based engineering is a Boeing digital transformation enabler, and a 2nd Century Enterprise Systems (2CES) initiative for Boeing. 2CES initiatives are key enablers for smarter certification using Digital Twins, and incorporate the elements captured in Figure 25.



2nd Century Enterprise Systems (2CES) Enabler:
- Common Architecture
- Methods, Processes and Tools
- Technologies and Innovations
- Data and Data Analytics

Product Development Digital Twins (PDDT):
- Airframe structure
- System Engineering
- Payloads and Interiors
- Propulsion Engineering
- Test and Certification
- Production system

Smarter Seat Certification Digital Twins:
- Structural Integrity
- Passenger Safety

Figure 25. 2CES Strategic Focus-Seat Certification Digital Twins

Model Based Engineering, or MBE, is a scientific approach to product development, manufacturing, and life cycle support that uses a digital model and product behavior simulations to drive first-time quality and reliability. The MBE Diamond shows integration of traditional product development approach along with 2CES, which will accelerate the design process through digital transformation, a simulated representation of a physical product development and certification.

10.2.5.1 Certification Requirements and Testing Digital Twins

Certification of passenger seats for installation on Boeing Commercial Airplanes requires compliance to 14 CFR 25.562, Emergency Landing Dynamic Conditions. The means of compliance is by dynamic sled testing, which demonstrates that the seat structural capability and occupant injury criteria have been met. The guidance listed in Advisory Circular (AC) 20-146, “Methodology for Dynamic Seat Certification by Analysis for Use in Parts 23, 25, 27, and 29 Airplanes and Rotorcraft” [48] provides guidance to seat manufacturers, airplane/rotorcraft manufacturers, and other applicants on requirements for using computer modeling analysis techniques. These Digital Twins are validated by dynamic tests, and are used to:

- Establish the critical seat installation location and configuration in preparation for dynamic testing.
- Demonstrate continued certification compliance when changes are made to a baseline seat design, where the original seat has established compliance based on dynamic tests.

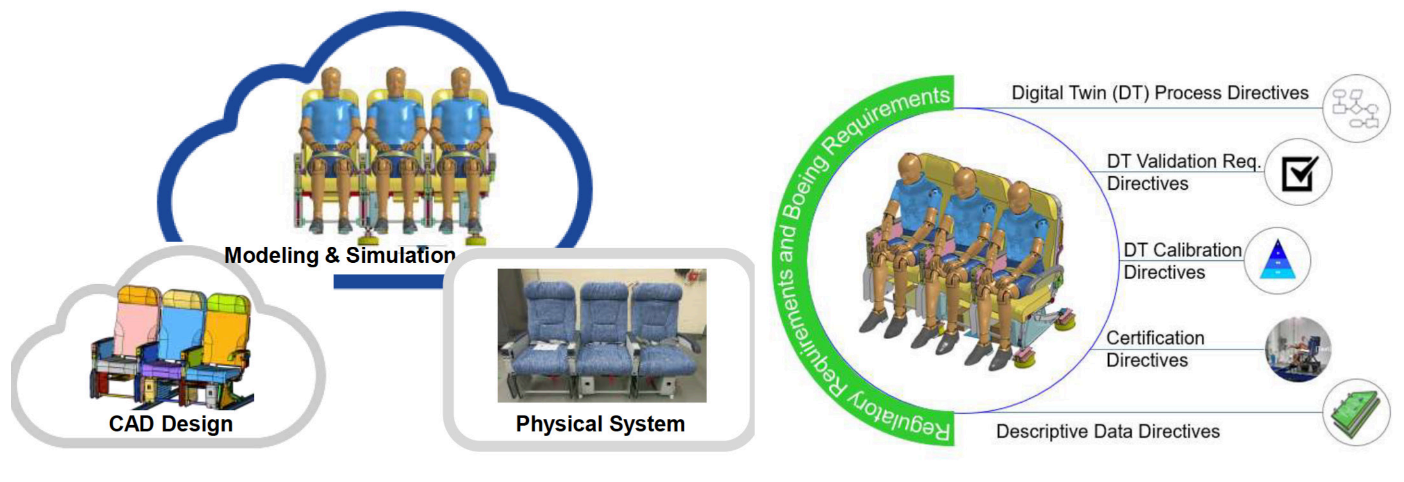


Figure 26. Certification path for seats using simulation with physical testing

The certification of Digital Twins (Figure 26) requires a robust methodology and processes where step-by-step modeling and simulation techniques are defined. The applicant is expected to execute and perform according to plan in order to minimize the influence of user experience and knowledge. This process should be presented to and demonstrated for regulators to ensure consistency and accuracy.

When the Digital Twin results are used to support the product life cycle, and when the Digital Twin is of significant consequence, the certification Digital Twin model must be validated to ensure it adequately captures the physical behavior of the real structure consistent with the model's intended use. Validation of a Digital Twin model evaluates the credibility of the model to ensure that it adequately captures the physical behavior of the real structure in a manner consistent with the model's intended use.

Certification and qualification directives state that it must be demonstrated that the predictive Digital Twin is accurate and that it adequately captures the physical behavior of the seat, including structural integrity and occupant safety performance. Documentation of model credibility is required as part of a dataset that allows regulators to review and approve the Digital Twin as part of certification.

10.2.5.2 Benefits of Digital Twins for Smarter Seat Certification Testing

Developing a high-fidelity Digital Twin model for seat system structural and passenger safety performance prediction demands consistency and accuracy throughout the numerical modeling and simulation stages.

Generating Digital Twins for seat certification could significantly reduce the number of required certification tests, with a 50% - 70% reduction in certification tests depending on the class of seats. This reduction is partly due to the use of simulations to address critical seat configurations, and partly due to a reduction in the number of failed tests, which then require redesign or rework.

10.2.5.3 Process Using Digital Twins for Smarter Seat Certification Testing

Implicit and explicit analyses have been used to evaluate dynamic response of seats, where each method has advantages and disadvantages. One advantage of the implicit method is that equilibrium conditions are checked at each increment of the analysis to ensure it falls within the required tolerances.

One major advantage of the explicit method is that the simulation is inherently stable from a numerical standpoint and is not subjected to issues of failed convergence that can occur with the implicit method. However, numerical stability does not necessarily guarantee reasonable or accurate solutions. Therefore, additional checks and sample validation simulations are needed to ensure that the modeling approach is sufficiently accurate to represent the structural response of interest.

Explicit solution-method codes typically output several energy values such as kinetic energy, internal energy, hourglass energy, and sliding energy. It is essential to check these energy outputs during the simulation to verify energy balance and whether the simulation ran properly.

For short-time duration analyses consisting of the nonlinear characteristics of seat dynamics, explicit methods are clearly recommended. Implicit methods for longer-time duration analyses may be more cost effective, depending on the importance of inertial effects, types of materials, and areas of interest.

Successful model verification, validation and error quantification are based on the building block approach, shown in Figure 27, which is a systematic approach of performing validation at several different levels of the modeling process starting with the material models up to the full-up system level model. This approach provides confidence in the validation effort between the full-up seat system dynamic simulations and the physical dynamic seat tests.

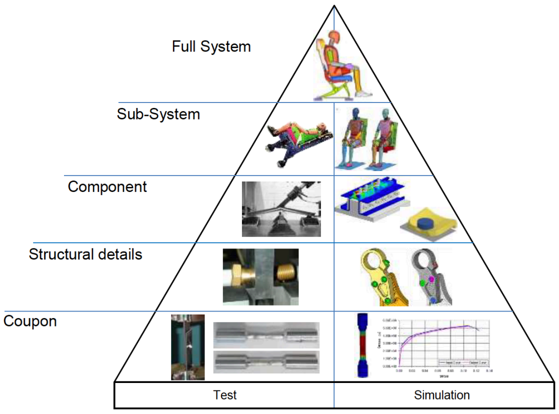


Figure 27. Building Block Approach for Dynamic Simulation

This approach also allows the applicant to understand the error, or variation between the digital simulations and physical tests that is present for each level and how it may affect the full-up seat simulations.

As shown in Figure 27, material characterization is the foundation of the building block approach. Accurate material models with the appropriate linear and nonlinear material properties help ensure successful validation. It is difficult to achieve reliable simulation results without high quality material data.

Selection of a material model depends on a number of factors such as the physical behavior of the material, how the part is loaded, potential failure modes, acceptable damage, etc. A material model should be chosen that represents the elastic-plastic material of the particular part in question. This may require additional coupon testing, validated with a quasi-static FEM to develop critical stress-strain curves of the material to support material model inputs.

10.2.5.3.1 Material Model Validation and Modeling Requirements

All models require validation, based typically on selected testing or on previous test-analysis comparisons. The building block represents parts and assemblies of increasing complexity, and validation ensures that the final complex combination of loading and structural responses is accurate, based on individual validation of selected loads and failure modes.

It may be necessary to conduct component level validation on structural elements to understand material behavior, stress concentrations, and failure prediction. This could include tension, compression, shear, or bending tests. Subsystem validation could include assessing joint response and stiffness of seat frame.

10.2.5.3.2 Typical Seat Structures and Components Digital Twins for Validation

Seat components are categorized by functionality and grouped into “modules.” The module concept can be useful during development of simulation models. Typical major sub-assemblies and associated components of seats are described below:

- Lower frame structure (legs, cross tubes, seat pan structure, spreaders, etc.)
- Upper frame structure (seat back, recline mechanism, seat back energy absorber)
- Seat cushions (bottom and back)
- Restraint system (lap belt, upper torso, end fittings, shackles)
- Items of mass (tray tables, foot rests, arm rests, IFE)

Subsystem validation can be used to determine structural strength as well as understand load distribution within components to evaluate deflection/deformation. Once material, component, and subsystem validation has been completed, a system level finite element model can be validated against a physical dynamic test.

Use of the building block approach allows for an assessment of the degree of accuracy at the system level. It is intended as validation of the material models used in the simulation, and is not to be used iteratively to calibrate the model. The calibrated material models and material parameters should be used in higher level of the building block. A high degree of accuracy at the coupon, component, and subsystem levels results in a high degree of accuracy at the system level.

However, the level of accuracy of test data should be considered when proposing validation criteria, as the fidelity of test data may vary with selected instrumentation. Also, all seat dynamic tests include some inherent variation associated with each physical test set-up. These variations might include for example the physical Anthropomorphic Test Device (ATDs), ATD positioning, lap belt pre-tension, pre- and post-test measurements, and camera set-up. Special attention and standardized test procedures are required to reduce test-to-test variability.

The typical system responses used for validation include: critical floor reaction loads, lumbar loads, lap belt loads, femur loads, head/knee trajectory, and resultant head accelerations. The validation criteria may include magnitude and time history. The validation plan should identify the appropriate validation criteria depending on the type of test and data to be collected. Figure 28 shows some examples of the certification tests that are simulated for all the seat families in a particular seat layout.

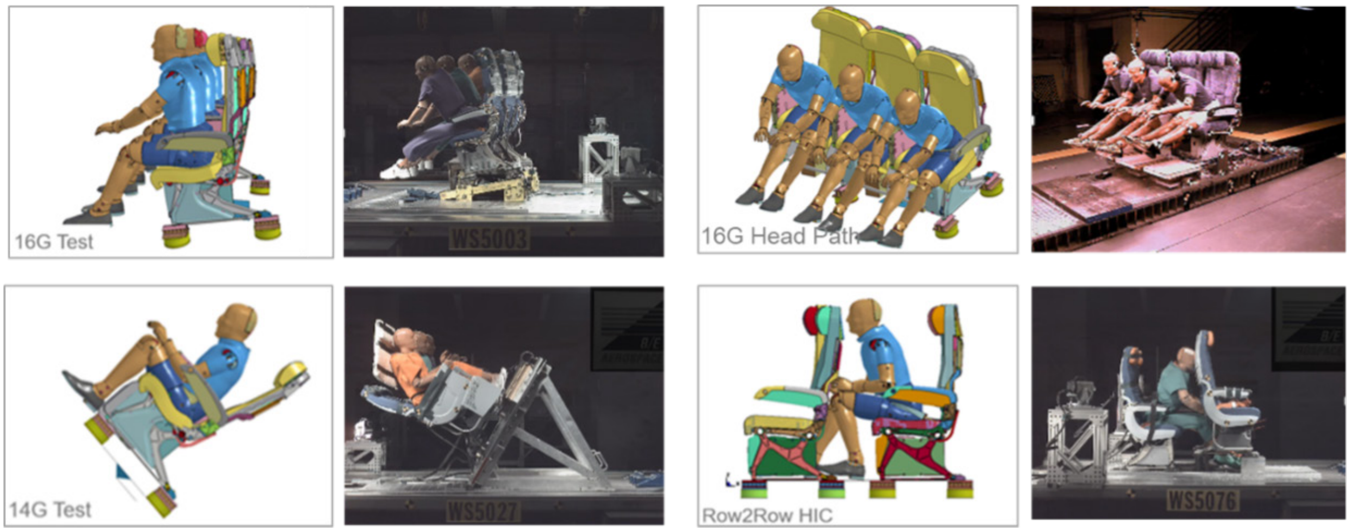


Figure 28. Several Digital Twins examples of the certification tests that are simulated

To date, the application of dynamic simulation to passenger seats has been used successfully to reduce the number of required certification tests. Proper application of analytical methods is now producing results that are of sufficient quality and predictability to reduce significantly the testing necessary for regulatory certification, and to produce superior seat designs more quickly. In the past, many of the certification tests depicted in Figure 28 are often conducted numerous times (typically each test type is repeated 2-5 times) to meet the requirements of a single economy class (E/C) seat program. With accurate and reliable dynamic simulation of these tests, it is possible to reduce each of these conditions to a single test. In summary, dynamic simulation Digital Twins have been used to drive smarter certification testing, first-pass quality, on-time seat installation, optimal design flow, optimal cost for seat design and certification, and above all enhanced passenger safety.

10.2.5.4 Lessons Learned

10.2.5.4.1 Illustration – Determine the Critical Seats Design Ranking

Typically, several different seat designs/families are identified for modeling and dynamic response simulation (Figure 29) to determine their critical ranking, based on peak loads or strain response. The simulation results then guide selection of the model validation tests. Usually, several analysts are involved in defining and generating a seat model, where each model is created according to the standard guidelines and methods. Even so, there are occasions when a model created by different analysts can diverge. The variation can be due to different contact definition, meshing pattern/quality, model penetration, or material model selections. This variation in model building is not uncommon, but can be eliminated by introducing a detailed model development plan for all the seat designs. Significant variability in simulation results would interfere with the seat ranking process, since the actual performance differences between designs may be masked by inconsistency in the simulation results. Thus, establishing a consistent and well-documented modeling strategy is an essential part of performing and validating seat simulations.

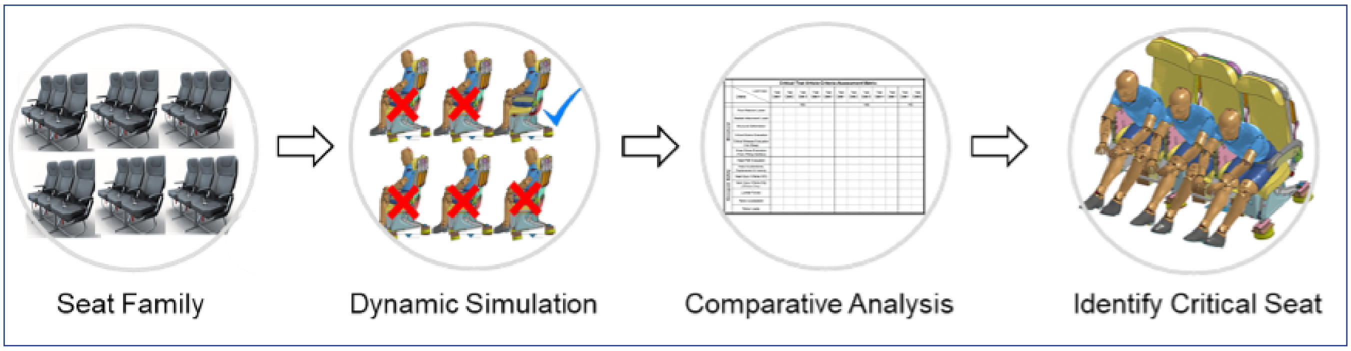


Figure 29. Selection of critical seat from family of similar seat designs

Performing parametric and comparative studies requires a consistent model development plan that follows a standard accepted methodology. The use of a model development plan and checklist ensures the repeatable, reliable, and consistent generation of models. This ensures that the primary load path structure and load transfer through the fasteners/joints will be correctly and consistently captured. Also, it was found that inconsistent definitions of fastened joints lead to differing deformation responses under the applied load conditions, leading to differing relative results. The following actions were introduced in the model development plan;

a. Ensure simulation model weight and CG conform to the design and are well documented.
b. Check to ensure loads and boundary conditions are consistent across the model.
c. For all primary load path structures - maintain a uniform meshing scheme.
d. Maintain element quality per guidance document with correct contact definitions.
e. Define consistent material properties, element formulations, and hourglass definitions.
f. Maintain consistent contact definitions for the entire seat model, including friction coefficient.
g. Define cross-sections to the primary load path structure to extract forces.
h. Maintain uniform simulation control parameters for all seat models.

Families of seats with a similar seat design typically have some minor design differences, but which have identical components in the primary load path. Seats within a seat family are based on the same design philosophy, method of construction, manufacturing processes, materials, and geometry. There may be minor differences due to spatial limitations and attachment methods. The creation of consistent models is essential to identifying the critical seat design ranking and to performing model validation.

The comparative simulation results for different seat designs show that the simulations performed by different groups of analysts will still predict the same order of criticality and response trends as shown in testing for reaction loads and deformation.

To select the most critical seat design for testing, the Digital Twin must be created following a standardized and documented procedure in which the digital model is validated with test data. This ensures generation of consistent and reliable results. The simulation model is a deterministic model, where model generation should follow a standardized model building plan to eliminate user-dependent variances, and to ensure repeatability of model creation. The model validation process ensures the accuracy of the model for certification of the seat.

10.2.5.4.2 Illustration – Verification and Validation for Deterministic Simulation with Test Variability

During 14g downward loading events as shown in Figure 30 and Figure 31, the dynamic simulation model response for ATD lumbar injury did not correlate accurately with the physical test results, even though the model was developed and analyzed following the standard guidelines. Testing variability was found to contribute to the test-simulation discrepancies.

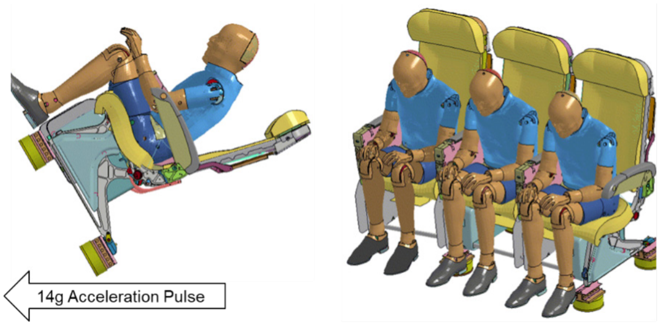


Figure 30. Direction of acceleration loading for seat with 14g pulse, applied 30 degrees from vertical

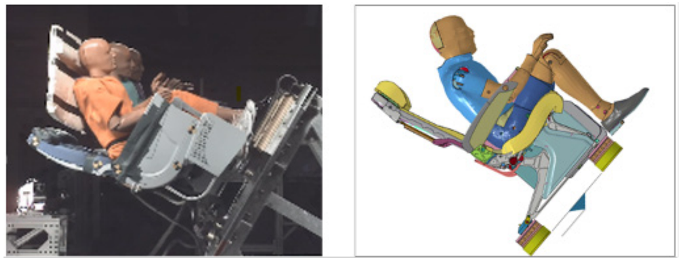


Figure 31. Typical ATD response during 14g downward simulation – all simulation ATDs have ideal position, test ATDs have random variations

The physical test and dynamic analysis correlation and model validation pose a challenge due to the deterministic nature of the model, as compared with the unpredictable and variable physical testing data. Deterministic models generate the exact same outcomes under a given set of initial conditions, whereas the stochastic nature of the test results lead to discrepancies in the test and analysis correlation.

Instead of validating the model with a single test result that is difficult to correlate, a better approach is to provide a rationale as to why the simulation and test data do not correlate within expected bounds, and to provide evidence of the degree of randomness of the test response.

Test-to-test variability cannot be eliminated, but it can be minimized with clearly specified testing guidelines. Significant test variability can interfere with the product development process hence interfering with model validation. Typical sources of test variability for seats includes the following:

- ATD-to-ATD variability: ATD calibration response differs with age and condition of the ATD
- Seat assembly-to-Seat assembly variability
- Test setup-to-Test setup variability: Occupant initial position with respect to seats
- Test setup-to-Test setup variability: Occupant initial position with respect to other occupants
- Test sled-to-Test sled variability: Consistent load and BC
- Stochastic nature of events during test: ATD's interaction

During test analysis, the correlation of each of these elements of variability was evaluated and documented, to show reasons for variations in the test response.

The nature of ATD kinematics and ATD-to-ATD interactions are unpredictable because dynamic crash events are inherently variable. This random response distribution may be analyzed statically but may not be predicted precisely with a single simulation. For example, in the sequence of events an ATD elbow may be obstructed with the seat, thus causing unexpected results. The obstructed elbow results in one ATD moving sideways, which changes the resulting lumbar loads, as seen from above in Figure 32. The deterministic model and stochastic nature of test responses can be explained by overlaying test and simulation images over time, for a qualitative comparison and review of results with the test video.

- At 200ms the hand of right ATD is trapped and the torsos of the center and right ATDs are rotating.
- The complex phenomenon is not repeatable either in test or simulation.
- Due to test variability, it is therefore not feasible to validated simulation with single test.
- Only left ATD shows ideal response, and only left ATD injury response is suitable for use in Digital Twin model validation.

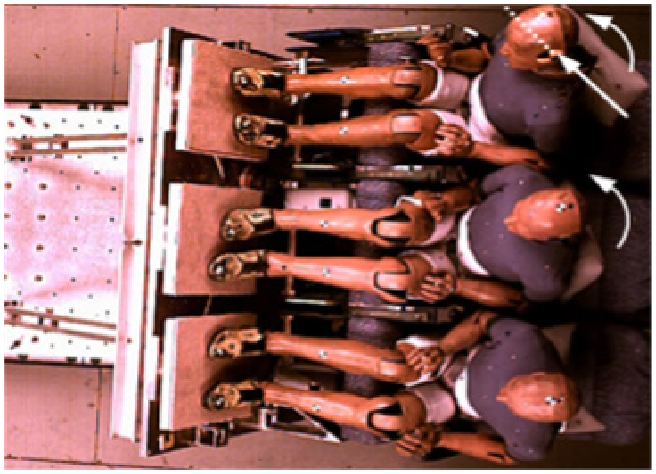


Figure 32. Random ATD response in test, rotation leads to lower than expected lumbar loads

While the left ATD lumbar load is correlated well with test, the Center and Right ATDs do not meet the 10% requirements. In this type of event, the demonstration of random test behavior and an appropriate rationale supported by analysis is required to accept the simulation results. By providing evidence of randomness of the physical test response in comparison with the ideal simulation response, it was possible to show that the simulation provided a reasonable and acceptable representation of the ideal event.

Model validation is deterministic, with a single test and one simulation. If the validation dynamic test experiences any stochastic (random) nature, it is difficult to meet the standard regulatory requirements of 10% correlation. The recommended approach when dealing with clearly stochastic behavior is not to correlate with a single test, but instead to provide a rationale as to why one response does not correlate between test and analysis. This involves providing evidence of random nature of the test response. This approach has been shown to be acceptable to regulators.

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10.2.6 Georgia Tech's Kendeda Building Digital Twin

A Digital Twin was created by the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech (GT) in support of GT's Kendeda Building for Innovative Sustainable Design (KBISD). Use of the Digital Twin made it possible for KBISD to receive certification in 2021 as a "Living Building" from the International Living Futures Institute (ILFI) [30]. Amongst other sustainability criteria, Living Building Certification requires that a building must be net-positive in its use of energy and water utilities over a 12-month period. This feat is challenging in Atlanta's hot, humid climate and because KBISD is meant for heavy use by the GT community for classes and events. A capability was needed to understand how KBISD's novel systems operate in an integrated fashion, subject to a variety of conditions. In particular, the Digital Twin was used to evaluate the building's actual performance, forecast future conditions, and explore alternative loadings and modes of operation.

10.2.6.1 Digital Twin Purpose, Users, and Use

Georgia Tech wanted to verify that KBISD was performing with high efficiency, as designed, so that it would be net-positive for water and energy in its first 12-month certification trial—as well as every year thereafter. The mechanical, electrical, and plumbing (MEP) systems of KBISD make net-positive performance possible. These include a photovoltaic canopy composed of more than 900 photovoltaic (PV) solar panels, a building envelope and mechanical systems 60-80% more efficient than conventional buildings, a water-saving composting toilet system, a 50,000-gallon cistern to collect rainwater, etc. Although its MEP systems were sized to gather a sufficient supply of electricity and water, it is still possible for system failures, suboptimal configuration, weather anomalies (e.g., heat waves or drought), or excessive internal usage to make demand exceed supply on a net annual basis. The Digital Twin needed to be subjected to the same conditions—weather, occupancy, control schemes—as its real counterpart in order to serve as a baseline for quickly detecting faults that would jeopardize certification. During the 12-month certification period, the Digital Twin was also used to forecast the net "budget" of water and energy through remaining months to gage whether the building might be "programmed" (i.e., planned) for more intensive use by occupants and visitors. A unique use case for the Digital Twin also arose when GT reduced its campus operations to safeguard against COVID-19 spread, leading to less occupancy in the building in 2020 than expected. In response, the Digital Twin was used to generate data quantifying the degree to which KBISD would have still been net-positive even during normal or even maximum occupancy through 2020.

The main stakeholders served by the KBISD Digital Twin were a Certification Team that convened throughout the phases of construction and commissioning of the building with the mission to resolve technical issues and ensure that the building performed as designed. The GT-external team members consisted of the original MEP design engineers, the construction firm and its MEP contractors, heating, ventilation and air conditioning (HVAC) controls engineers, data platform and building automation system (BAS) vendors, and commissioning engineers hired to test the building's integrated performance during start up. The GT-internal team consisted of KBISD's director and building manager, engineers from the design and construction (D&C) and operations and maintenance (O&M) groups in GT Facilities Management, and the ASDL researchers, who served as the architects of the Digital Twin and participated in Commissioning and Certification meetings. The questions from the stakeholders the Digital Twin aimed to help answer can be categorized as descriptive (e.g., “Is KBISD performing as expected?”), diagnostic (“…and if not, why not?”), predictive (“Will KBISD certify as net-positive given its current trajectory this year?”), prescriptive (“How might we operate it more efficiently?”), and scenario-based (“Would KBISD still have certified as Net-Positive if in-person classes hadn’t been suspended?”).

10.2.6.2 State of the Industry and Challenges with Respect to Digital Twins of Building Operations

Modeling practices in the building architecture, engineering, construction (AEC) industry largely support design and construction (D&C) phases of the life cycle. CAD modeling for AEC has in recent decades evolved to more descriptive Building Information Modeling (BIM), used to manage the maturation of architectural concepts into fully specified construction documents. Besides 3D representation of a building’s design (geometry and materials), BIM can be used to track and manage cost and scheduling aspects (“4D” and “5D”, respectively) during the construction phase. Post-construction, BIM can be used for keeping track of building assets and space use. Full BIM models tend to be impractical for use in mirroring energy and water operations, although a reduced set of BIM geometry, with less detail, is sometimes extracted for use in dashboards or in analysis of building energy system designs. For that latter purpose, Building Energy Models (BEMs), which represent building physics, are used to ensure that designs meet codes and standards for energy efficiency and performance (e.g., thermal comfort for occupants). At higher fidelities, BEMs can be used to design and test control strategies.

Challenges exist regarding the practicality of utilizing BIM and BEM beyond D&C phases as a Digital Twin for evaluating the performance of building water and energy systems in operation. One reason is that fidelity of D&C BIM/BEM models are too high for practical calibration to as-built systems and/or require operational data at granularities that are not cost-effective to collect and manage. This operational data includes measurements of building conditions (external and interior) and the system states (including sub-metering of energy and water by end use). The variability introduced by occupants’ use of a building introduces further challenges to match modeled energy and water performance to reality.

In general, the return on effort to calibrate Digital Twins of building performance can be unattractive, especially when compared with that of other systems like vehicles. The return (or value) is relatively lower because performance requirements around building utilities (e.g., efficiency, comfort) tend to be less demanding than those of vehicle operations (e.g., safety) and thus attract less investment. The effort required to model a building’s energy systems and to calibrate those models is also considerable. The types of, quality of, and standards for data describing building operations are often mixed and not well inventoried for legacy buildings. Changes in a building’s use over its life (e.g., as operation levels increase, new entities take over the space, etc.) extend the effort required. Finally, the architectures and uses of different buildings are often very diverse, so the potential for model or data reuse across a community of buildings can be limited.

Research and industry groups are actively addressing the aforementioned challenges to making Digital Twins practical and cost-effective for evaluating the energy performance of buildings. Pilots, like the one explained subsequently, are clarifying their value, streamlining their creation, and giving examples of how to choose appropriate levels of model fidelity suited to various needs.

10.2.6.3 Digital Twin Context & Scope

The ASDL research team developed requirements for the Kendeda Building Digital Twin by engaging weekly with the KBISD Certification Team for over a year. To certify as a Living Building, it would need to be demonstrated that KBISD could, on a net basis, generate ≥5% more energy using PV panels and collect ≥5% more rainwater using catchments and cisterns than was consumed by the building’s loads. This ultimately can be verified by actual data after the 12-month period, but a means was needed to verify on an ongoing basis that the building was performing as expected. If the building were consuming its energy and water budgets too quickly—whether due to inefficiency, excessive loading by occupants, extreme weather—the Certification Team could take corrective action rather than risk needing to restart the 12-month period of net-positive certification. Conversely, if the building were exceeding expectations of efficiency, even more visitors and events could be encouraged, thereby maximizing KBISD’s value as an inspiring, educational space for the campus community as well as a visible technology showcase.

Two major modes of use for the Digital Twin were identified. First, simulations using the Digital Twin needed to output data about building performance (e.g., energy and water production and consumption, indoor air conditions) that reasonably match those measured from the real building, when subjected to the same input data (e.g., weather, occupancy, control schemes followed by the building's MEP systems). This mirroring supports assessment of whether the building is performing as expected. Second, simulations using the Digital Twin should yield reasonably accurate results for alternative inputs, i.e., conditions that the building could realistically experience, although not necessarily observed a priori. These results were used for "what if" situations to forecast where the building would end up with respect to being at least 5% net-positive as well as try out other modes of operating MEP systems.

The ASDL research team worked closely with the Certification Team in order to design, build, calibrate, and use the Digital Twin. Before KBISD's construction, ASDL studied construction documents and created a "proto-twin", a parametric model capturing the physics of the system as designed, before operating data were available. These models provided a means to calculate net-positive performance under different historical years of weather. During KBISD's construction Phase, ASDL examined the MEP systems as they were being built in order to evolve the parametric models and understand the nature and quality of data sets gradually coming online. These activities catalyzed discussion in commissioning meetings and even allowed the ASDL team to flag data errors in need of correction. During the Commissioning Phase of Summer and Fall 2019, ASDL began to calibrate the integrated Digital Twin, first for warmer seasons. Model evolution and calibration continued as the Living Building Certification period began in December 2019. At this point, ASDL served as analysts of KBISD's integrated performance, using the Digital Twin and presenting its results in an interactive manner to the Certification Team. This would continue through KBISD's successful certification as a Living Building in the spring of 2021. As campus operations changed in Spring 2020 due to COVID-19, the Digital Twin was used to simulate scenarios of operating the building in modes that would be more energy efficient under reduced occupancy. These were implemented and used to improve the model's accuracy. In late 2021, ILFI, the group that certifies Living Buildings, announced that it would accept model-generated data in addition to real-world data in applications for certification. This meant that it would evaluate the real 12-month performance of a building lightly occupied due to COVID-19, even though it might be perceived as having had an easier path to certifying. To address that criticism, ILFI also allowed the use of models, calibrated to real data, to substantiate whether the building still would have been ≥5% net-positive for water and energy under normal or even maximum allowable occupancies. GT's Digital Twin of KBISD was influential in ILFI deciding to augment its certification criteria for the special circumstances of 2020.

10.2.6.4 Identification/Collection of Data & Models: Model Approach, Choices, and Development

A Digital Twin can be described in terms of its virtual representation (i.e., models), data fed to it via measurements from the physical system, and a user interface to support comparison of the Digital Twin to reality. For the Kendeda Building use case, these elements are overviewed in Figure 32. To realize a Digital Twin that could support the usage modes described in the previous section, proper scoping of data and modeling was necessary. Technically, there were two Digital Twins for the Kendeda Building, encompassing water and energy aspects, which relate to each other; only the latter will be discussed henceforth. The energy twin accounts for energy inputs (solar and ambient thermal inputs, which depend on weather conditions) and energy "end use" loads, which were, roughly in descending order of magnitude: HVAC (typically the main consumer of electricity), plug loads (office equipment, servers, etc.) lighting, domestic hot water heating, and systems unique to KBISD, e.g., composting exhaust fans, water treatment, etc. Sub-meters for all of these end uses were installed during the building's construction and made available to ASDL via a SkySpark-based data platform. Data was sampled historically at intervals as small as every 5 minutes. Data describing the state of systems (e.g., HVAC) and indoor air conditions were also available, typical of points collected by modern Building Automation Systems (BAS). ASDL was also careful to ensure the accuracy of weather data, including solar irradiance, humidity, temperature, etc. Further, ASDL collected data on occupancy of the building over the 12-month period, which was found to be an essential input to calibrate the model sufficiently. ASDL devised an API-based means to connect the Digital Twin to all of this data.

To represent energy system behavior, ASDL devised a reduced-order building energy modeling (BEM) approach [49]. The approach employs a reduced-order representation of thermal behavior of the building in aggregate. It was initially based on an accepted ISO Standard (ISO13790:2008) [50] for calculating building energy but heavily augmented with custom modules for more accurately capturing heat exchange and employing data-driven models for several of the energy subsystems (e.g., plug loads). This approach allowed for calibration of the models with available data, avoiding the difficulties associated with high fidelity BEM (e.g., used in the Design phase) mentioned in previous sections. Model tuning factors were selected that could make the Twin's outputs match the building's response variables shown in the right side of Figure 33. Several months of iterations were needed to adjust the model fidelity for the different energy end uses, including finding correct tuning factors suited to different seasons. The final model, implemented in Python, is used in simulations of the macro-level energy performance of the building as well as the interior conditions (e.g., temperature) being maintained. The simulations can either utilize actual data from the Twin's real counterpart or alternatively use weather, occupancy, or other loading inputs to stress-test the building virtually in order to investigate the effects on net-positive performance. The simulations execute in under a minute due to the use of models purpose-built with fidelities suited to macro-level studies of energy performance

An interactive user interface was created to overlay actual data and modeled outputs, aiding the process of model creation and parameter tuning. This user interface was further adapted to present results of the twin to the KBISD stakeholders for use in periodic investigations of the building's performance.

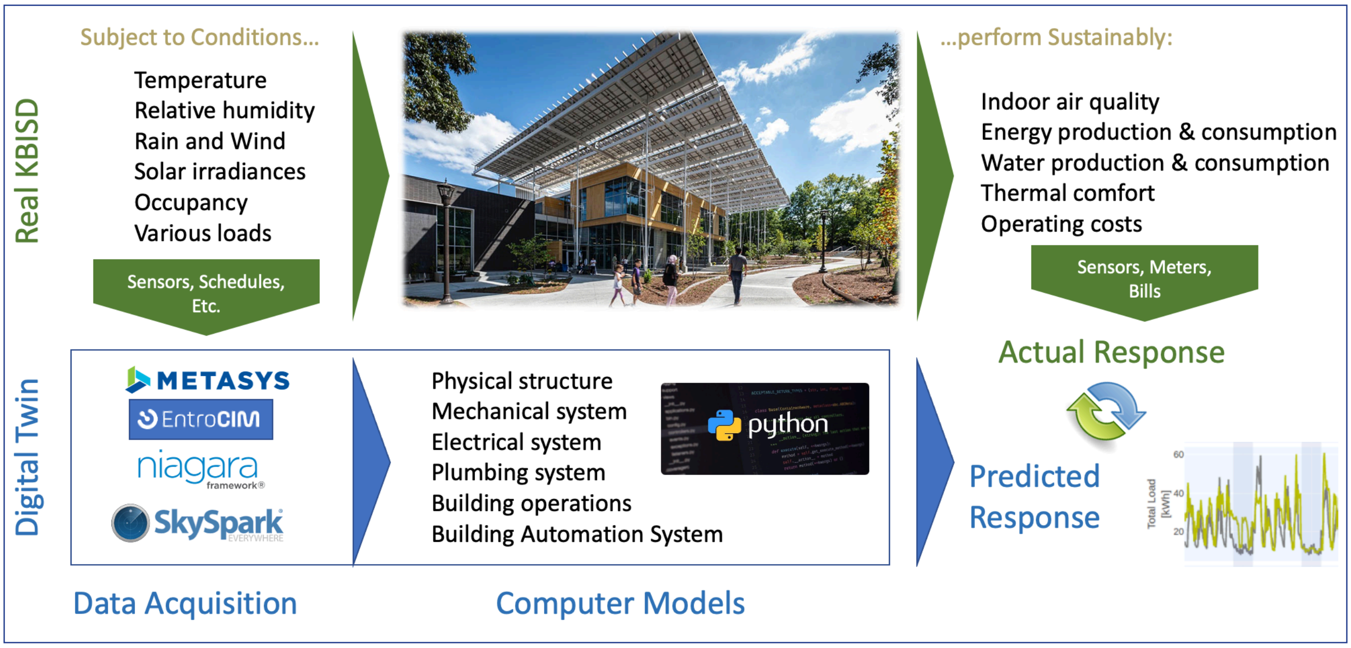

Figure 33. Kendeda Building for Innovative Sustainable Design (KBISD) and Its Digital Twins

10.2.6.5 Implementation

The implementation of the Digital Twin —specifically a reduced-order, physics-based model which can take inputs of operational data measured from the real system— involved the following steps:

- Understand the as-built KBISD system
- Measure actual performance: the inputs and responses in Figure 33
- Model the as-built system
- Integrate models into a Digital Twin and calibrate to observed performance, iterating as necessary by increasing fidelity, exploring alternative modeling approaches, etc. until good convergence
- Employ the Digital Twin on a periodic basis in reviews with stakeholders, to:
    - o Benchmark performance to identify system and/or data degradation
    - o Run scenarios subjecting the twin to alternative inputs, to answer "what if" questions.

10.2.6.6 Lessons Learned

The lessons learned as part of developing a Digital Twin of the Kendeda building relate to both stakeholders and modeling & data:

- Stakeholders
  - o Active engagement and formal communication with all stakeholders are key to the successful development of Digital Twins. A common challenge is to obtain stakeholder buy-in from the outset. Oftentimes people need help understanding the value brought forward by Digital Twins.
  - o Armed with a first Building Digital Twin and realizing its value in certifying the KBISD building, stakeholders will be more favorable to the replication of the effort across other buildings on campus
- Modeling & Data
  - o Significant portions of the knowledge needed for modeling is tacit, in the minds of SMEs, who use it to generate ideas about tactics and operational options.
  - o Model fidelity should be adequate for the purpose of the Digital Twin
  - o More fidelity requires more data--which will likely never materialize (or have low ROI).
  - o While working with the KBISD Team as a means to understand the available data and determine modeling requirements, ASDL researchers uncovered issues with data quality and building operational performance, even before the completion and calibration of the Digital Twin.
  - o Challenges with data included:
- Realizing that "typical" choices for sensors or meters yielded data with quality good enough for traditional maintenance, but not sufficient for Digital Twin calibration. Likewise, traditional measurement and verification (M&V) processes might not catch these data deficiencies.
- Standards and naming conventions for sensors and metering data are essential to avoiding mislabeling, which can complicate calibrating models and even accurately assessing how the system is performing.
  - o Whereas there were members of the KBISD team responsible for IT, commissioning, etc., it was observed that none were explicitly charged with ensuring the quality of data. ASDL recommends the creation of a Chief Data Office position to help alleviate some of the issues encountered.
  - o Calibration is an ongoing process, since buildings can change greatly over time.

10.2.7 Digital Ghost – Cybersecurity for Critical Assets Leveraging Digital Twins

10.2.7.1 Background

Many critical infrastructure assets within the US, such as power plants, transmission and distribution networks, transportation systems and water processing plants, are efficiently and safely operated using control systems. Such control systems act as the "brains" of the plant or asset reading information from sensors and sending command signals to actuators. Control systems are also critical subsystems in mobile assets such as aircraft, automobiles and even locomotives. Keeping the control systems safe and operational without degrading performance even during cyber-attacks attacks is becoming a national imperative with the growing number of sophisticated cyber-attacks aimed at disrupting operation or damaging assets [51-54]. The "Digital Ghost" technology described here contributes to a defense-in-depth strategy by adding a radically innovative approach to attack detection and asset resiliency.

Increasingly, control systems are being connected to the internet or other communication networks for the purposes of remote monitoring and diagnostics, visualization of key performance data, or even to allow new software applications to optimize asset performance. This concept of connecting assets and their controllers to other assets and machines across various locations is often termed the Industrial Internet, Industrial Internet of Things (IIoT), Industry 4.0, or the Internet of Things (IoT). This connectivity allows the remote deployment of new software applications and the ability to keep the compute platform updated with the latest virus definitions and software patches; however, it could increase the risk of malicious cyber-attacks that can disrupt operation to the point of even destroying or harming the assets and associated systems. Even when the asset is "air-gapped", meaning no direct external communications connection is made, clever attackers have managed to use human behavior to help "infect" their targeted equipment. Recent events have shown the vulnerability of key infrastructure systems to cyber-attacks, only reinforcing the need to continue developing more sophisticated protection methods [51-54].

10.2.7.2 Technical Approach

Digital Ghost is a solution to the physical defense layer protection system [55-58]. Key system monitoring nodes are used to continuously screen the state of a system. The generic framework uses as many heterogeneous sensors (signals, logicals, etc.) as available, all simultaneously, and is applicable to any physical system with inputs and outputs, with and without feedback. High speed control system data is transformed from the time domain into feature space where it is more efficient to determine if a system has been attacked. An attacker may spoof the time domain data (e.g., streaming sensor measurements) but it is much harder to spoof the inherent physics relationship of the system as seen in the feature space.

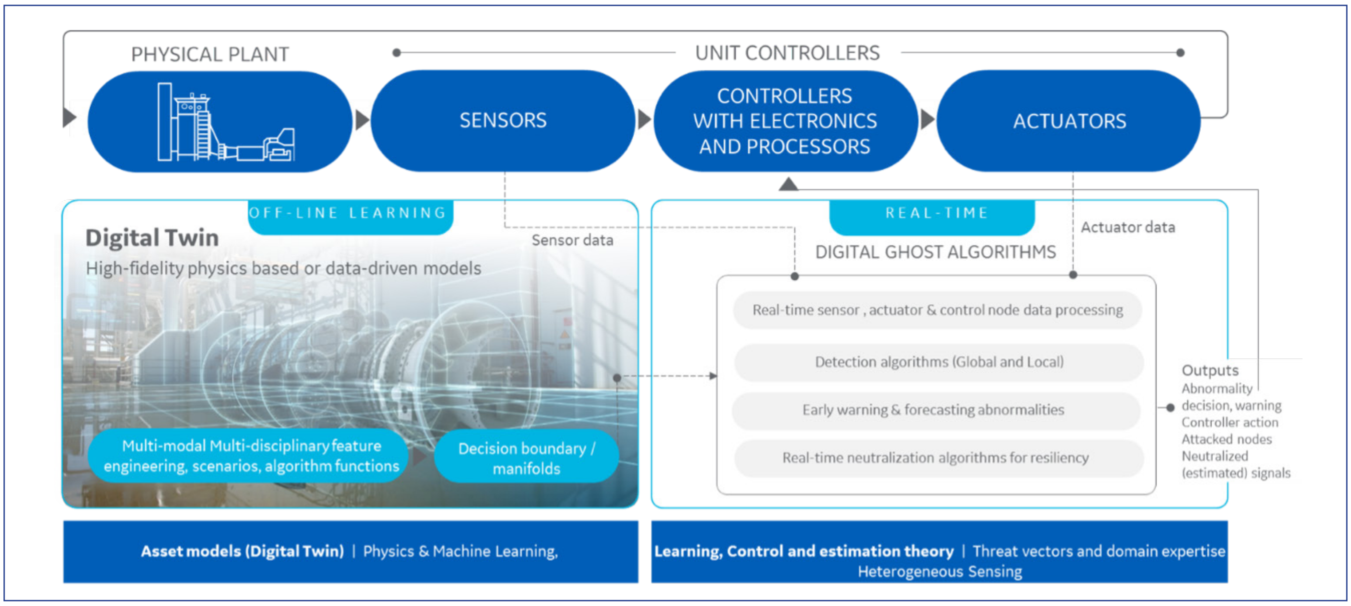

Figure 34. Digital Ghost functionality diagram. Example is of a power generation plant. The top portion in the figures depicts a complex system with sensor, controls, and actuators. The bottom left pane shows how the Digital Ghost algorithms are trained from off-line operational data and Digital Twins. The bottom right pane outlines the real-time algorithms providing detection and neutralization functions when deployed.

The Digital Ghost (DG) cyber-physical security and resiliency system consists of three main functionality modules [58-60]:

Detection: Determines if an abnormality from normal operation occurred.

Localization: Determines what is under attack or has faulted, in terms of monitoring nodes (i.e., sensor, actuator or control nodes). It also provides forecasting, early warning capability and critical real-time insight into system operations so that operators can monitor malicious activities, tampering of control system parameters, or potential onset of a fault.

Neutralization for resiliency: Maintains the integrity, operability, and availability of the system without degrading the performance (i.e., curtailment), or commanding a controlled emergency shutdown using estimators with inputs from monitoring nodes. While the system is operating with the neutralization function, agile response teams and other intrusion/fault response capabilities can be deployed to manually triage the event.

Thus, using the integrated system, if an attack is detected, it will be quickly localized to the offending node. Once localized, the impacted system operation is modified with a neutralization algorithm that effectively replaces the corrupted functionality with an uncorrupted estimate, keeping the system online and maximize the availability even while attacks are in progress. In broad terms, Digital Ghost framework provides the ability to neutralize the effects of abnormal events even when a very large number of monitoring nodes are attacked. Operators are alerted when a cyber-attack/fault detection has occurred, where it has occurred, and the corrective action required to keep the system active while producing output. Figure 34 shows the Digital Ghost functionality diagram. Collectively, these described features provide self-healing capability to help create an attack-immune and resilient system.

10.2.7.3 Differentiation Based on Digital Twin

At its core, the Digital Twin consists of sophisticated computer models or system of models based upon deep domain knowledge of specific industrial assets. The Digital Twin is informed by a massive amount of design, manufacture, inspection, repair, online sensor, and operational data and employs a collection of high-fidelity computational physics-based models and advanced analytics to forecast the health and performance of the asset over its lifetime.

The accuracy of the Digital Twin's representation grows over time as more data refines the model and similar assets are deployed with their own Digital Twins. Data are gathered continually to maintain an up-to-date model. Digital Twin models include all necessary aspects of the physical asset or larger system including thermal, mechanical, electrical, chemical, fluid dynamic, material, lifing, economic, and statistical.

For example, the Digital Twin of a power plant can pull in data from multiple systems including sensors and controls as well as remote systems to get key operating data like weather forecasts. The Twin knows how the plant is configured and models the thermal efficiency of the system and the specific condition of plant components with respect to life and operating efficiency. As the plant is operated, the Twin continually improves its ability to model and track the state of the plant. The Digital Twin can be incorporated into the Digital Ghost system to allow and understand normal operation based upon the physics of the plant and distinguish when abnormal behavior is underway from a potential cyber-attack.

The models most often incorporated inside a Digital Ghost represent the thermodynamic laws of physics, energy balance and mass balance. Virtual Digital Twins of the unit controller software are used in conjunction with the asset models. Together these models and virtual controller software provide a faster than real-time environment to test normal operations and cyber-attack scenarios.

The high-fidelity Digital Twin allows simulation of a wide array of operating conditions and foreseeable attack vectors to train the Digital Ghost with the highest fidelity. As mentioned before, mere historical data is not sufficient for this purpose as it will mostly contain normal operation data over a limited operating regime. Thus, utilization of Digital Twins really provides OEMs like GE with the edge to learn high dimensional decision boundaries required to achieve the high accuracy for critical applications.

10.2.7.4 Conclusion

Critical infrastructure assets are now key targets for cyber-attacks. By connecting the control systems running the infrastructure assets to outside communication networks, the Intranet, new services such as remote diagnostics and prognostics can be realized helping increase availability and even performance. However, this comes at the risk of exposing the assets to cyber-attacks. GE has developed a totally new ecosystem for cybersecurity/fault protection focused on the concept of a Digital Ghost monitoring an asset's behavior always checking for anomalous events and then sustaining operations through its advanced neutralization technology. If detected, the Digital Ghost can act immediately to locate and neutralize the effects of the attack or fault allowing the system to continue operation or perform a graceful shutdown. More research, however, is needed to make the algorithms inside the Digital Ghost robust and to apply this technology to different use cases and cyber-attack/fault scenarios across multiple critical infrastructure asset types.

10.2.8 Iron Bird Digital Twin

10.2.8.1 Iron Bird Digital Twin

Building an aircraft has three main phases: design, manufacturing, and testing. Testing an aircraft is essential and testing accuracy is extremely important. Making these tests under almost real and accepted conditions by the authority is needed for certification and to validate the design. Hundreds of test environments are being used during an aircraft validation and certification activities. Turkish Aerospace designs and builds aircraft from scratch and develops the Flight Control System (FCS) as a subsystem with all system engineering and software development activities. Turkish Aerospace is also responsible for the integration of aircraft on the final assembly line and for the completion of aircraft level testing. An Iron Bird is one of these test environments and is an essential tool to validate and verify FCS with actual actuators, hydraulic system, and loads. An Iron Bird mainly consists of a flight control system with real actuators, harnesses, software and computer, and hydraulic system with all actual components. An Iron bird also has a loading system including hydraulic, loading actuators and controllers. An Iron bird mainly applies real loads to control surfaces with different parameters for different flight conditions. The FCC and hydraulic system are being tested under real load conditions as well as with some hard-failure cases (actuator jam, hydraulic failure, etc.) Testing flight control algorithms with software in the loop and hardware in the loop test environments represent the general approach. Using an Iron Bird and testing the Flight Control System under real loads with actual mechanical and hydraulic system is essential for a fly-by-wire system. Actuators are important and valuable equipment for the aircraft industry. They are essential to the ability to control the aircraft. Actuators are also important for test rigs to provide enough power through a requested direction. Actuators and the hydraulic system are the heart of the Iron Bird. Flight control algorithms are being tested in a desktop development environment with a generic actuator model with generic backlash and stiffness parameters. To assess the action of the Flight Control System and observe how stiffness, backlash, and load affect its behavior, almost 1000 hours of flight testing is being run on an Iron Bird. As such tremendous amounts of data are being collected during Iron Bird testing activities. Turkish Aerospace is experienced with updating hydraulic and actuator models with real data as a means to provide a better and realistic testing environment on the desktop for flight control software. As such the decided to create a Digital Twin of the Iron Bird and other test rigs. The Iron Bird Digital Twin concept provides continuously updating of generic actuator and other mechanical system models with the help of actual data, which is being collected during each test. Establishing a real-time connection between sensors on the Iron Bird and the Digital Twin environment provided Turkish Aerospace with an environment to test generic actuator and hydraulic models with real test input and to update their models. Actuator and mechanical system behavior may change with time and with different environment conditions but having an updated model for these systems will also help to modify or update current air platform more effectively even in design phase. From a certification perspective, having an Iron Bird and using it for thousands of hours of flight is still essential. In addition, decreasing the number of failed tests on the Iron Bird with the help of the Iron Bird Digital Twin will provide effective usage of the test rig and decrease the time needed to complete Iron Bird essential tests. This approach will help engineers to validate their design in earlier phases.

10.2.8.1.1 Flight Control Systems

The Flight Control System (FCS) consists of a set of hardware and software that allow the pilots to keep the aircraft's heading and attitude as requested with his commands or inputs from the auto pilot control panel. Flight control systems are mainly divided into primary and secondary systems. The primary systems are necessary for the safe controlling of the aircraft and basically consist of the aileron, elevator, and rudder systems. Secondary control systems are systems aimed at improving the performance of the aircraft in general. Computer-based flight control systems also consist of the flight control computer, pilot controls, electrical power supplies, hydraulic components, sensors, and actuators. In the Flight Control System, which is referred to as fly-by-wire, all inputs of the pilot are carried to the flight control computer as electrical signals. Computers then compile the data received from these commands and sensors and send generated commands to the actuators. A general diagram of flight control system components is presented in Figure 35.

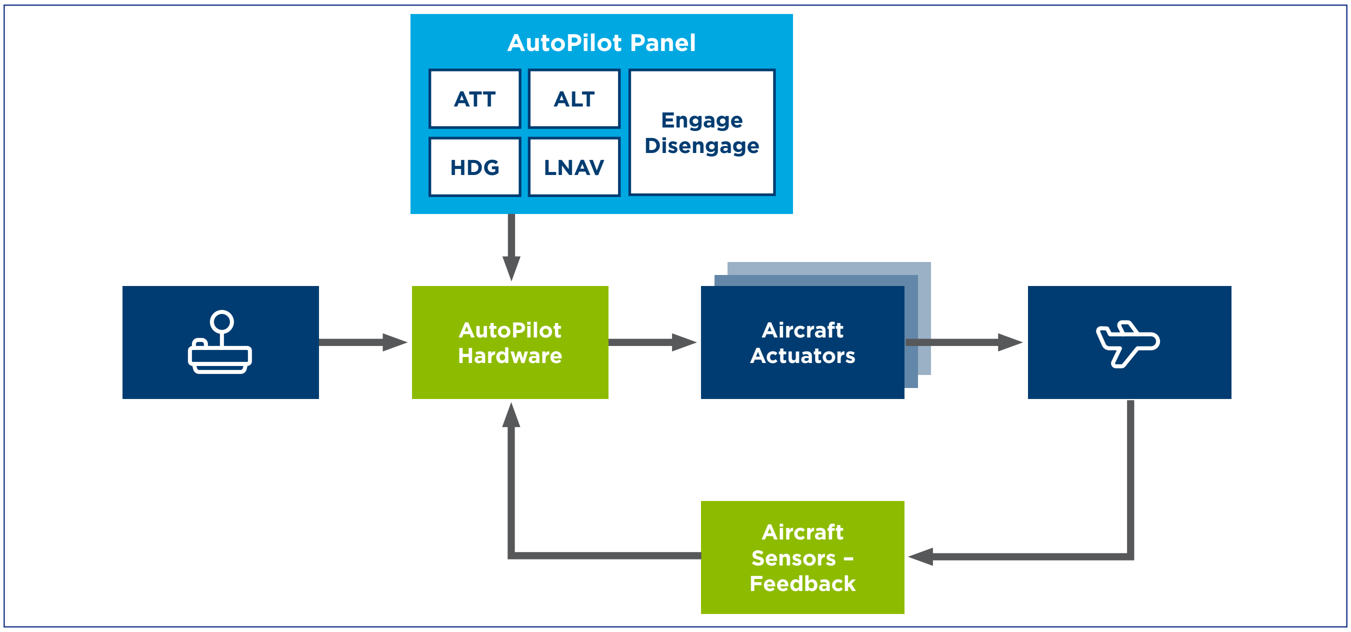

Figure 35. General Block Diagram of Flight Control System

The development and verification of the Flight Control System (FCS) are being conducted in a desktop environment by using a modeling tool or as code based. Some models used in this development environment, such as the actuator, stiffness, and backlash models, are needed to develop and test the FCS and are generally standard and generic models. Some of these models are being provided by the manufacturer. The Iron Bird is a fully integrated test environment with a loading system capability developed for the flight control system to assess the real effects and interaction of these components with developed flight control algorithms and logics. The Iron Bird Digital Twin provides an environment to monitor and update these component models continuously and serves as a capability to run desktop tests very accurately for the next testing or development activities. These improved and verified models are called trusted iron bird models and will also be used to validate any newly added feature to the FCS.

10.2.8.1.2 Iron Bird

The Iron Bird is the environment in which the flight control system is completely tested with real equipment and real loads. The Iron Bird is explained in detail in SAE AIR5992 - Descriptions of Systems Integration Test Rigs (Iron Birds) For Aerospace Applications [61]. According to the SAE document, when the development of “Systems Integration Test Rigs” occurred simultaneously in same test rig with the development of hydraulically powered flight controls, it is called generically as “Iron Birds.” A generic block diagram of an iron bird test rig and facility is given in Figure 36 and the general structure of the Iron Bird captured in Figure 37.

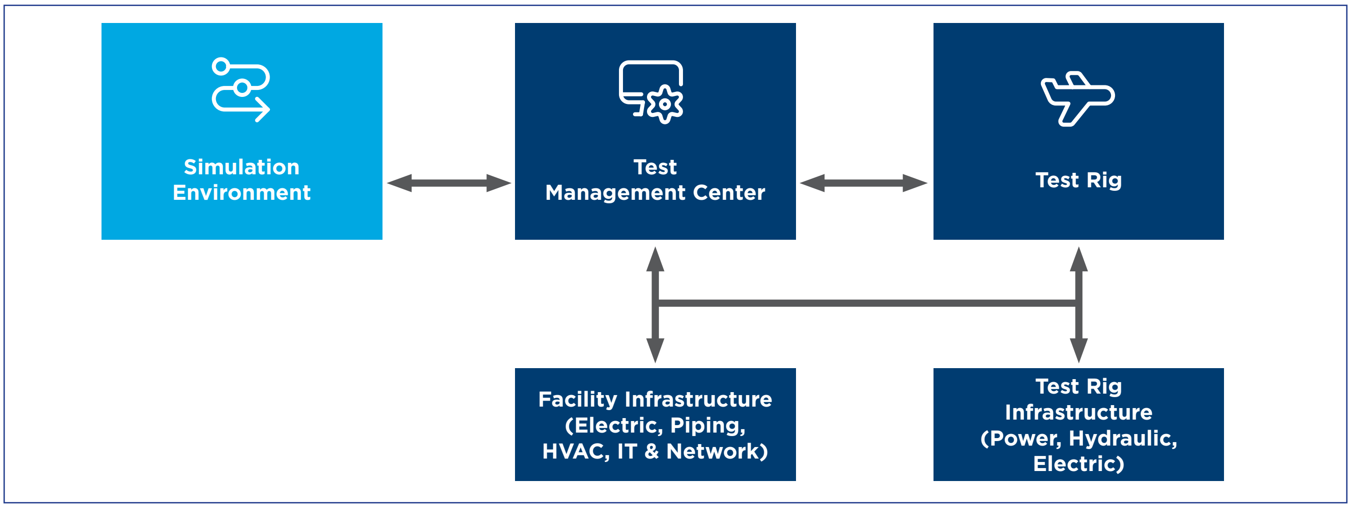

Figure 36. General Diagram of an Iron Bird Test Rig and Facility

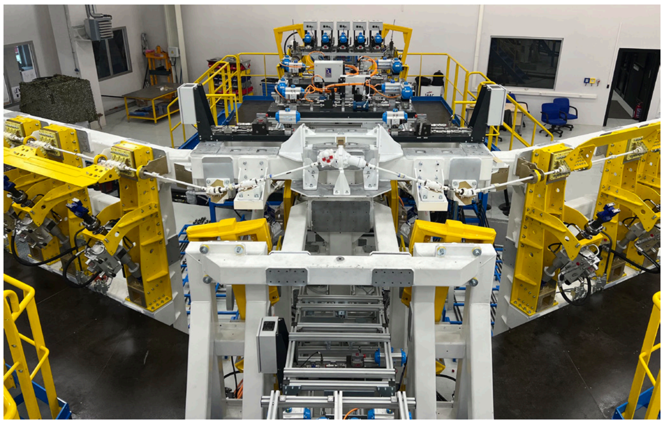

Figure 37. General Structure of an Iron Bird

One of the most important components of the Iron Bird is actuator and actuator driver systems, including the controllers. Actuators are important and valuable equipment for the aircraft industry as they are key to the ability to control the aircraft. They are fastened to the aircraft structure on one side and the aircraft surfaces to be controlled with the other side. There are many factors that affect the movement and reaction of the actuator. These are basically hydraulic, surface material, backlash in fasteners, stiffness, and loads applied to the surface in the air or on the ground. The Iron Bird has a loading system with dynamic loading capability. The loading system has a separate hydraulic system and loading actuators and controllers. The

Iron Bird is an integrated environment with actual aircraft components and test rig components. Aircraft components include the flight control computer, sensors, control surfaces, harness, hydraulic equipment, and test rig components, including the control and management software, loading system, measurement sensors and avionics equipment. The Iron Bird test rig capabilities allow for the control surfaces and FCS to be tested under real air conditions. An advanced flight control system is first being tested over mathematical models in the development environment. It is then tested with generated software and integrated hardware in the system integration laboratory (auto pilot system integration lab) as software in the loop and hardware in the loop test. In particular, the testing of the developed controller algorithms and logics in which the system is housed is critical for the performance and safety of the aircraft.

One of the parts of the Iron Bird is the test management center (TMC). TMC manages all testing activities from the generation of test scenarios to the generation of test reports. TMC is communicating with the simulation environment in real-time and gets related data from models run in the simulation environment to drive the test systems. Sensor models and aerodynamic models of the aircraft are some of these models. The TMC also runs and manages the test rig and obtains generated data to drive the simulation environment as well as monitors and records all data collected from the Iron Bird and simulation environment. The Iron Bird should be active during the aircraft life cycle. The amount of data generated from this test rig is huge but also very important to validate the system and to find the source(s) of problems that may occur in the future. The test rig infrastructure for the electrical power and hydraulics is the same as in the aircraft.

10.2.8.1.3 Digital Twin Concept for Iron Bird

Although the main goal is to create a Digital Twin of an entire aircraft to serve the aviation industry and academia, one of the preferred and efficient methods is to start by creating Digital Twins of subsystems. When it comes to create a Digital Twin, besides the models and physical system, a means to collect data from the physical system and a connection to this data source is needed initially. When it comes to creating a Digital Twin of an aircraft, the Iron Bird represents a good testing environment because it presents all the critical components of the aircraft. The Iron Bird also represents a huge source of data as it includes almost 150 sensors to drive and control the system. These data can help support the development of data-driven models for the Digital Twin environment. To that end, Turkish Aerospace designed a big data system integrated into the Iron Bird that parses the huge amount of data in real time and publishes the parsed data to requested subscribers in a software framework during test running activity. This system has four worker servers that run in parallel and one master server which controls the system. The system passes parsed data to the Digital Twin framework and this data is being used to run simulations. Figure 38 shows the data parsing and storing system block diagram.

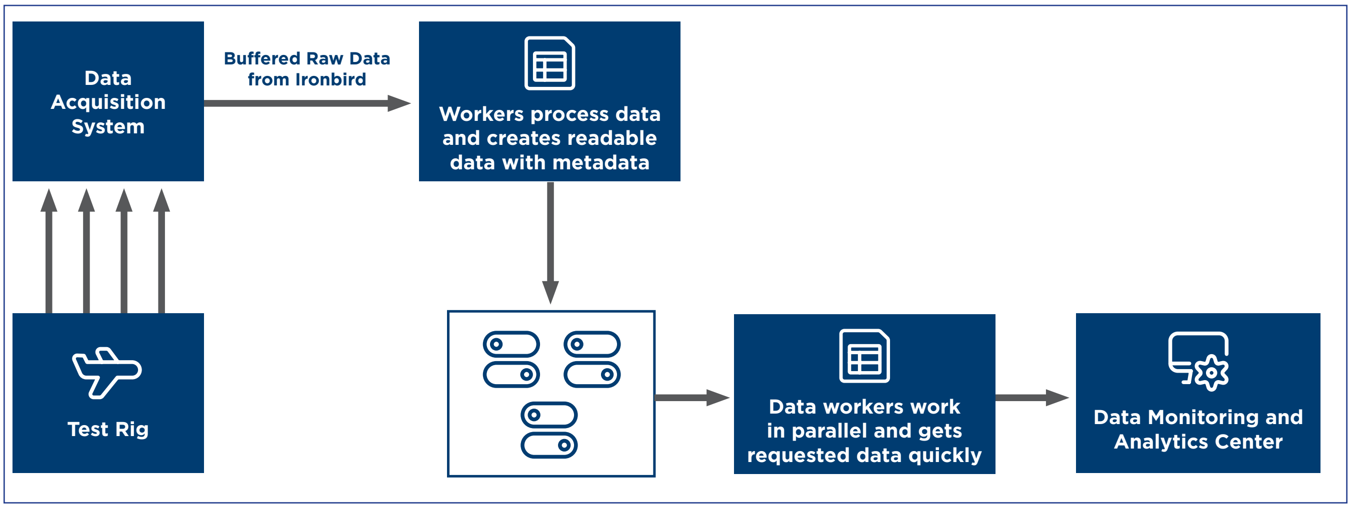

Figure 38. Iron Bird Data Parsing and Storing System

To complete the Digital Twin of the Iron Bird, the components the flight control system is interacting with are first modelled with a modelling tool. The generated models are then integrated into the Digital Twin framework as pure code able to run in real-time. Real FCS codes are also integrated into this framework along with real-time data sharing provided between them and other components' models. As mentioned, the Iron Bird is a huge test rig and consists of hydraulics, FCS, electrical systems, landing gear and mechanical systems. To validate an encompassing Iron Bird Digital Twin is very challenging which is why Turkish Aerospace decided to generate trusted models for each sub-component step by step. To validate the Digital Twin framework concept and approach, a control surface actuation system was selected as a sub-component of the Iron Bird. To control this surface on the real aircraft and on the Iron Bird, the FCS generates a command. This command is then being processed by the actuator control system and the actuator moves to control the related surface. The aircraft's hydraulic system gives power to this actuator to generate movement. The surface's angle and load applied to this surface's actuator are being measured and data is being sent to the aircraft verified aerodynamic model and sensor models which run in the simulation environment. Outputs of these models are then being processed again by the FCS and according to the new situation the FCS generates a new command. Figure 39 shows the aircraft flight control surface as fastened to the Iron Bird's structure with real actuators. The blue ones are also loading actuators.

Figure 39. Control surface, aircraft actuator, and loading actuator installed on the Iron Bird

For the Iron Bird Digital Twin concept, extra sensors are added to this surface to update stiffness, backlash, and actuator models according to real-world test data. The Iron Bird also has the capability to modify its environmental conditions. For example, the Iron Bird has a heating blanket to be able to change the environmental conditions of the equipment. When any actuator runs on the Iron Bird, the input data of this system is being used in the Digital Twin environment and outputs of the systems (real and Digital Twin) are being compared. After examination of the results, engineers may decide to update the models or parameters, as relevant. The Digital Twin concept may also include an automatic model selector algorithm. The actuator and mechanical system behavior may change in time but having an updated model for these systems will also help to modify or update current air platform more effectively even during the design phase. The Iron Bird Digital Twin will help to have these updated and validated models. Figure 40 illustrates the Iron Bird Digital Twin concept framework.

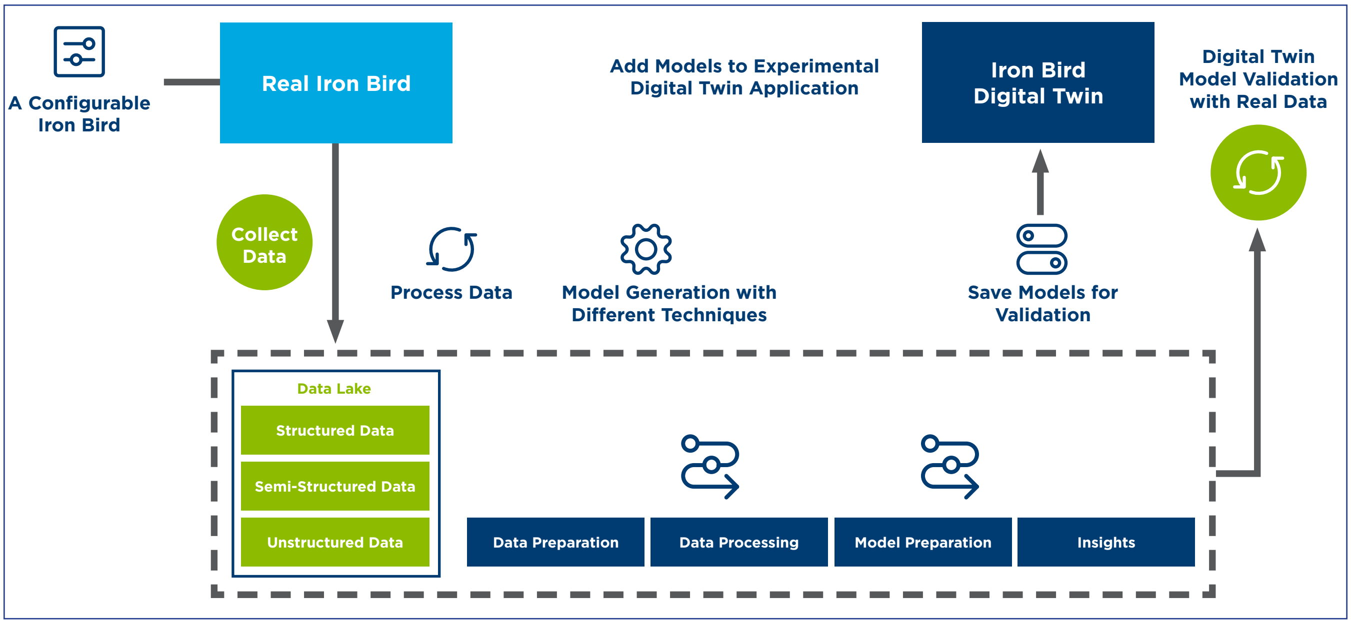

Figure 40. Iron Bird Digital Twin Concept

These updated and verified (called trusted) models generated by using the Digital Twin are being used in the desktop development environment or the system integration lab to test, debug or improve FCS functions. These models will also help to develop better systems for the next version/generation of aircraft. These trusted models may also be stored in a Product Life Cycle Management (PLM) system for change management and made available across the company to be used in other applications. From a certification standpoint, while having an Iron Bird and using it for thousands of hours of flight is essential, decreasing the number of failed tests on the Iron Bird using the Iron Bird Digital Twin will provide effective usage of the test rig and decrease the time needed to complete Iron Bird essential tests. This approach will help engineers validate their design effectively in earlier phases of the design. Finally, the Iron Bird Digital Twin concept may be used for any test rig due to its flexible and proven structure.